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Interim Report

STABILIZATION OF THREE TYPICAL INDIANA AGGREGATES USING FOAMED ASPHALT

TO: H. L. Michael, Director
Joint Highway Research Project

November 17, 1981

FROM: Leonard E. Wood, Research Engineer
Joint Highway Research Project

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Attached is an Interim Report "Stabilization of Three Typical Indiana Aggregates Using Foamed Asphalt", which is a part of the HPR Research Project titled "The Use of Foamed Asphalt in Bituminous Stabilization of Base and Subbase Materials and Recycled Pavement Layers". Mr. Humberto Castedo, Mr. Robert Shofstall and Rodolfo Gonzalez, Graduate Instructors in Research authored the report and conducted the study under the direction of Professors Leonard E. Wood and A. G. Altschaeffl.

This report presents a detailed laboratory study concerning the development of a design procedure for foamed asphalt mixtures and the feasibility of stabilizing three typical Indiana aggregates using foamed asphalt. The variables studied were three levels of bitumen content, three levels of moisture content, three curing periods, two levels of test temperature and three levels of mixing temperature. The foamed asphalt mixtures investigated in this study produced satisfactory cured strengths, but were susceptible to water damage. It appears that foamed asphalt can be used as a stabilization agent when adequate drainage and sealing are provided.

The report is offered as partial fulfillment of the objectives of the Research Project and will be submitted to IDOH and FHWA for review and acceptance.

Respectfully submitted,



Leonard E. Wood
Research Engineer

LEW/cer

cc: A. G. Altschaeffl	D. E. Hancher	C. F. Scholer
W. L. Dolch	K. R. Hoover	K. C. Sinha
R. L. Eskew	J. F. McLaughlin	C. A. Venable
G. D. Gibson	R. D. Miles	H. P. Wehrenberg
W. H. Goetz	P. L. Owens	L. E. Wood
M. J. Gutzwiller	G. T. Satterly	E. J. Yoder
G. K. Hallock		S. R. Yoder

Interim Report

STABILIZATION OF THREE TYPICAL INDIANA AGGREGATES USING FOAMED ASPHALT

by

Luis Humberto Castedo Franco
and Robert Lawrence Shofstall,
Graduate Instructors in Research

Joint Highway Research Project

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The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification or regulation.

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16. Abstract <p>In this laboratory study, the effects of different factors on the properties of foamed asphalt mixtures were investigated. This laboratory study was also concerned with the development of a design procedure for foamed asphalt mixtures and the feasibility of stabilizing three typical Indiana Aggregates using foamed asphalt. The variables studied were three levels of foamed asphalt content, three levels of moisture content, three curing periods, two levels of test temperature and three levels of mixing temperature.</p> <p>The foamed asphalt mixtures investigated in this study produced satisfactory cured strength but were susceptible to water damage. It appears that foamed asphalt can be used as a stabilization agent when adequate drainage and sealing are provided.</p> <p>A design procedure for foamed asphalt mixtures was recommended from the findings of this laboratory investigation.</p>			
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LIST OF SYMBOLS

AC	- Asphalt Cement
C	- Cohesimeter Value
CBR	- California Bearing Ratio
h	- Specimen height, in.
HBP	- Hot Bituminous Pavement
%B	- Percent Bitumen (dry weight basis)
γ_d	- Dry Density (pcf)
LVDT	- Linear Variable Differential Transformer
M_R	- Instantaneous Resilient Modulus (psi)
M_S	- Marshall Stability (lbs.)
P_h	- Horizontal pressure in stabilometer
P_v	- Applied vertical pressure in stabilometer
SSD	- Saturated surface dry
%FA	- Percent Foamed Asphalt Content, expressed as percent by weight of the dry aggregate.
%W	- Percent Initial Moisture Added (Mixing Water), expressed as percent by weight of the dry aggregate.
%WR	- Percent Moisture Retained in the sample at time of testing.
%MA	- Percent Moisture Absorbed during water saturation.
%TL	- Percent Total Liquid at time of testing (%TL = %FA + %WR).
UW	- Wet Unit Weight of compacted specimen.
DUW	- Dry Density of compacted specimen.
FM	- Mixing Temperature.

LIST OF SYMBOLS (Continued)

FT	- Testing Temperature.
S	- Hveem Stabilometer Value, (S-value)
R	- Hveem Resistance Value (R-value)
D ₂	- Displacement of stabilometer fluid necessary to increase horizontal pressure from 5 to 100 psi (34.5 to 689 kPa), measured in revolutions of a calibrated pump handle.
P	- Marshall Stability, measured in lbs.
F	- Marshall Flow, in 1/100 inch.
S _t	- Marshall Stiffness = P/F
V	- Specimen volume (ft ³)
V _{RI}	- Instantaneous resilient vertical deformation
W _A	- Weight of asphalt (gm.)
W _S	- Dry weight of aggregate (gm.)
W _T	- Total specimen weight (lbs.)

HIGHLIGHT SUMMARY

A detailed laboratory investigation was performed to characterize the performance of foamed asphalt as a stabilizing agent. The objective of this study was to develop guidelines for a mix design procedure. The effects of different variables on foamed asphalt mix design were investigated using AC-20 as the bituminous material, and outwash sand, pit run gravel and crushed stone as the aggregates. The variables being studied were: bitumen content (3 levels), moisture content (3 levels), curing period (3 levels), testing temperature (2 levels), and mixing temperature (3 levels).

Foamed mixtures were prepared by introducing foamed asphalt at 325°F to moistened aggregate at room temperature. After a mixing period of approximately 2½ minutes, specimens were fabricated using the California Kneading compactor. Following an appropriate curing period, foamed specimens were tested for Hveem resistance, modified Hveem stability, modified Marshall stability, and resilient modulus. The effects of water on foamed mix performance were also investigated using the water sensitivity test. The results from all of these tests were interpreted in such a fashion that a mix design procedure was recommended for use with any foamed asphalt mixture.

The behavior of foamed asphalt mixtures was greatly influenced by testing temperature. Strength values for all tests were significantly larger at the lowest testing temperature. Foamed mixes were also

found to be significantly affected by water infiltration. Water sensitivity results indicated that saturated strengths were much lower than corresponding cured strengths. Specimens fabricated at the highest bitumen content showed a greater resistance to water. In addition, moisture content (at mixing), bitumen content, and the total fluid content all proved to have an effect on mixture performance. Foamed mix strength also increased with curing time, particularly from 1 day to 3 days.

The foamed asphalt mixtures investigated in this study produced satisfactory cured strengths, but were highly susceptible to water infiltration. It appears that foamed asphalt can be used as a stabilizing agent when adequate drainage and sealing are provided.

INTRODUCTION

Engineers have long realized the economical advantages inherent to aggregate stabilization. In general, stabilization has as its purpose the improvement of the behavioral properties of the material being stabilized. These properties can be strength, compressibility, permeability, flexibility, workability, and others. In road work considerations, stabilization is often thought of in the context of improving subgrades or subbases, so as to reduce pavement thickness requirements for given loading conditions.

Many stabilizing agents are presently in use, including: portland cement, lime, lime-flyash and bitumen. This paper will investigate the feasibility of a relatively new bitumen stabilizer known as foamed asphalt.

The foamed asphalt concept was developed during the mid 1950's by Professor Csanyi of Iowa State University. The potential benefits from this process appeared to be so numerous that interest quickly spread. The applicability of the foaming process is currently being studied and evaluated throughout the world, in countries such as: Australia, South Africa, New Zealand, Japan, and West Germany. In Australia alone, over 3½ million square yards of foamed asphalt has been laid down, generally as a base or subbase. Foamed asphalt construction has also increased in North America, as hundreds of miles of surface course mixtures have been produced (37).*

*NOTE: Numbers in parentheses refer to the Bibliography of this report.

When cold water is introduced to hot paving grade bitumen, a foamed asphalt is produced. This foamed product has a lower viscosity and a larger effective volume than the penetration grade bitumen originally used. The foaming process offers several economical and environmental advantages over competing bitumen stabilizers. From a production standpoint, less water is hauled and less asphalt is required than in the use of an asphalt emulsion. Therefore, significant energy and transportation savings are realized. Additionally, curing of the compacted mix is not required, therefore the roadway can be opened much more quickly. It should also be noted that the curing process is environmentally safe since no harmful hydrocarbons will pollute the atmosphere. Another process benefit is that foamed mixes allow a broader spectrum of aggregate. Marginal soils containing large amounts of fines, often deemed poor for other types of stabilization, are usually quite suitable for foamed asphalt stabilization. Foamed mixes have also been found to be very workable. If necessary, the mix can be reworked several days after compaction to achieve specified densities. A major plant advantage is that foamed mixes can be stockpiled. Foamed asphalt mixes reportedly can be stored up to a year without any detrimental effects (31).

Presently, most studies on foamed mixes are concerned with developing a mix design procedure. This study approaches mix design using strength data obtained by Hveem techniques and the resilient modulus test, among other test parameters.

The major concern of this report is the performance and production of bituminous stabilized bases using commonly available materials in the

State of Indiana, by means of the not so well known technique of foamed asphalt stabilization.

The foamed asphalt stabilization permits the combined use of the most prominent factors related with both cold and hot mix methods. By using the asphalt cement as a foam and not in its liquid form (heated), augments its volume as much as 13 to 20 times (11). Less quantities of this material are expected to be required to achieve the same characteristics as those obtained from conventional hot mix. The use of cold wet aggregates will eliminate the use of energy required for drying processes.

However, due to the complexity of the mix behavior under different loading and environmental conditions, a more thorough understanding of the role of each of the foamed asphalt stabilized bases components is needed. The goal of this study is to provide the necessary information to enable the Indiana State Highway Commission to utilize mixtures stabilized with the foamed asphalt process.

REVIEW OF THE LITERATURE

The primary objective of this section is to review the development and reasoning behind the use of foamed asphalt as a stabilizing agent. This relatively new concept appears to exhibit several interesting characteristics which could lead to increased use of locally available materials without some of the detrimental features associated with other agents.

Approximately 20 years ago, the process of foaming asphalt was developed by Csanyi (1959), who used low pressure steam injected concurrently with the asphalt to generate a foam, prior to its contact with the aggregate. About 1970 an improved patented system was developed by the Mobil Oil Corporation. The original process was slightly modified in an effort to simplify field control practices. The modified procedure, which is most often used today, involves the introduction of cold water under a controlled flow rate into hot bitumen. A foamed state is produced when approximately two percent cold water is added to hot (325°F) penetration grade bitumen in the foaming chamber. The water instantly produces a frothy asphalt with an effective volume 8 to 15 times greater than its original volume (50). The asphalt generally remains in the foamed state for a short period of time, usually between 15 and 60 seconds depending on temperatures and control rates used.

The foamed asphalt process has been used successfully in Australia and South Africa as a stabilizer. Colorado has begun a development program for the use of foam asphalt in base and subbase materials. A recent resurgence of interest in the foamed asphalt process was initiated by the development of advanced procedures for foaming the asphalt used in laboratory investigations, as well as in field works. Foamed asphalt as a bitumen stabilization agent is still a relatively new process. Few references and only recent field applications of this technique may be found in the literature. Nonetheless, the existing publications all positively attest to the potential usefulness of this stabilization agent.

Foamed asphalt stabilized base is a mixture of wet unheated aggregate and asphalt cement mixed while the asphalt cement is in a foamed state. The most common procedures used for bituminous stabilization are compared below with the foamed asphalt technique. (After Frank Abel) (2).

TABLE 1 - Asphalt Cement Mixing Methods.

	Aggregate	Asphalt Cement	Laydown	Haul	Special Processing of Asphalt
Hot mix.	Hot	Hot	Hot Dry	Asphalt 100%	No
Emulsion mix.	Cold	Cold	Cold Wet	Asp. 50%-70% Water 40%-30%	Yes
Foam mix.	Cold	Hot	Cold Wet	Asphalt 100%	No

In order to predict how a pavement material treated with foamed asphalt may behave in service, it is necessary to either study its

response in actual pavements under traffic or environmental conditions, or to employ laboratory tests which attempt to simulate the stress conditions observed in the field. The instrumentation of field experiments is difficult and require long periods of time to produce responses that can be related with the performance of the pavement. Laboratory tests usually provide the more rapid and comprehensive means for characterizing pavement materials. Nevertheless, an accurate simulation of the pavement conditions is necessary in order to obtain meaningful predictions from a laboratory experiment.

Reviews of research studies performed in Iowa, Colorado, California and Texas, as well as Australia, South Africa and other countries, provide a broad range of data from a variety of aggregates and test procedures. Generally, the different methods of investigation cover the selection, proportioning and testing of the components involved in the production of foamed asphalt paving mixtures. The aggregate characterization, the determination of different asphalt cement's foaming characteristics; the selection of the variables that will be measured proportioning, mixing, preparation and curing of the samples; are the different steps and sequences followed in most of the reported studies performed for foamed asphalt mixtures.

Abel, in his most recent report (2) recommends that "...soils and aggregates intended for use with foamed asphalt should be examined individually. Soils with high plasticity index (P.I.) are difficult to mix with foamed asphalt. Soils with medium PI would mix well, but showed high moisture susceptibility...Small amounts (1.0 to 2.0 percent) of additives such as portland cement or hydrated lime may be

useful to reduce the effect of PI, and improve the quality of stabilization".

Twenty one different foam bitumen stabilized sands were investigated by Acott (3) who found that in general "well graded sands had higher stability", however, a poor correlation was found between gradation of this material and strength parameters. Acott (3) quotes that "...low stabilities were obtained for the particularly dirty or clean sands, and a filler content of between 5 and 14 percent should be considered as the main grading requirements".

Aggregates and soils intended for use in foamed asphalt mixtures, generally should be tested to determine: gradation, Atterberg limits, specific gravity, maximum density and optimum moisture content (OMC) according to Standard AASHTO T99 procedure. These parameters, will help in the determination of the suitability of the mineral aggregate for its intended use with the foam asphalt application. They also provide minimum information required for determining the resulting density of the foamed mixture, its void contents and to establish liquids content on the mix. As stated before, in the first section of this chapter, the determination of the "fluff point" of the material is considered by some investigators, for mixing moisture content of the mix. However, a highly plastic soil or material could be stabilized with foamed asphalt by adding small amounts of portland cement or crushed stone filler (22), and as reported by Abel (1), the foamed asphalt process can use stockpiled-rejected mineral materials processed on a commercial basis that had no utilization for these large amounts of rejected aggregates.

Nevertheless, Abel (2) also recommended that "...is not economical to utilize well-graded good quality material with this process because hot mixes made by using good quality aggregate are significantly better than the foamed asphalt mixes".

The testing of asphalt cements for adequacy of foaming should be performed in the laboratory prior to the utilization of this material. There are no records to suggest any asphalt cement that can not be foamed by the Csanyi's process or the modified one. It seems that this effect is always possible by proper selection and adjustment of nozzle and proper steam, water, air and asphalt pressure, according to the method being used. Information concerning the foam properties of asphalt cements is often reported in terms of foam or expansion ratio (ratio of foam volume to the volume of the asphalt cement before foaming), and half life of the foam (the time that elapsed from the moment that the foam was at its maximum volume to the time that it reached half of this volume).

In 1978, Abel (1) concluded after analyzing asphalt cements of different viscosities and from different sources, with and without anti-foaming agents (silicone), and anti-stripping additives that:

- Asphalts with silicone do not foam satisfactorily.
- The lower viscosity asphalts foamed more readily than the higher viscosity asphalts.
- Anti-stripping additives increased the foam factor (expansion ratio), however, this effect appeared to be temporary probably because high heat tends to destroy most anti-stripping agents.
- Asphalt cement temperatures have to be at least 300°F (149°C) to produce acceptable foam.

It is clear that the source, viscosity (grade), additives and temperature of the asphalt cement can all affect the characteristics, quality and quantity of the foam produced. Brennan (11) in a study conducted at Purdue University in 1980, reported similar findings. In this report, expansion ratio (foam factor) and half life were measured to compare the foaming characteristics of different asphalts from various sources. Half life and expansion ratio were affected primarily by the amount of foam produced, the amount of water in the foam, and the foaming temperature of the asphalt.

In general, increasing the foaming temperature increased the expansion ratio but at the detriment of the half life. The increment in the amount of water used to foam the hot asphalt cement had the same effects. Therefore, a trade-off of half life for expansion ratio or vice versa, was suggested (11) for the selection of the most suitable asphalt cement to be used in foamed asphalt mixtures as a stabilizing agent.

"Reasonable" limits for expansion ratio, 6 to 12, and half life of 40 to 80 seconds are reported and recommended by Mitvalsky (31). Brennan selected from his investigation (11) asphalt cements with expansion ratios as high as 20, and half life around 30 seconds. Expansion ratio/half life ratios of 4.5/105s, 9.0/55s and 13/20 sec., are normally encountered in the literature (2, 11, 31).

Several studies have been performed to compare foamed asphalt mixture properties with those of conventional hot mixes especially.

The factors that influence the response of granular materials stabilized with viscoelastic binders such as asphalt cements and other bitumen applications are listed and evaluated elsewhere (refer to

Section 4), therefore, their principles and significance will not be discussed here, and only some quantitative as well as qualitative results will be presented. While discussing the test results obtained in his investigation, Abel (2) reported that "...In most cases the foam asphalt mixes show higher stability and modulus values than the hot mixes when samples are cured the same way. However, the foamed asphalt mix is much more susceptible to water damage..." This appears to be the most crucial and relevant disadvantage of foamed asphalt mixtures, reported in almost all the studies where water susceptibility of the mixture was observed. Quoting Abel again, some suggestions are found: "Experience here has shown that lean emulsified asphalt stabilized aggregates respond in about the same way to the immersion-compression test and the free-thaw test...Less severe moisture susceptibility tests need to be developed for a relative rating of foamed asphalt mixes".

Different aggregates, soils and mineral materials were used in producing foamed asphalt mixtures. As expected, each granular material performed differently. Typical values for foamed asphalt with 3, 4 and 5 percent of foamed bitumen content were found by Mitvalsky (31) to be 41 to 72 for Hveem stabilities and near 95 for Hveem Resistance values "...All values are well above normally specified limits". Using Mobil Oil of Australia test procedures (12) in the preparation and testing of the samples, Mitvalsky (31) found that "...S-values at 3% asphalt content were equal to that of a hot mix prepared with the same aggregate at 5% asphalt content. However, cohesiometer values were found to be inferior for foamed mixtures when compared to hot mixes, but were still above the normally specified limits (7)".

Abel (2) in 1979 reported his findings in a study where comparisons between hot mixtures and foamed asphalt mixes were made using North Dakota base course aggregates, "...the same amount of asphalt content was used in each type of mix, and foamed asphalt specimens showed better or the same properties as hot mix samples". The same density of the compacted specimens, 2.49, was reported; higher Hveem S-value and R-value, as well as cohesiometer values were obtained for the foamed asphalt mixture. However, these specimens gave only 24% of retained strength after soaking for only one day at 77°F (25°C), compared with 86% retained strength for hot mix samples subjected to a more severe test, (4 days at 120°F (50°C).)

Mitvalsky (31) reported that foamed asphalt specimens failed to retain their good properties after vacuum saturation and explained that "...the causes of this failure were not determined. Unsuitability of the aggregates used for foam mix stabilization, or the inefficiency of the foam asphalt process above, remained unanswered". All samples with foam asphalt contents less than 5%, didn't withstand the water saturation test.

Parameters measured in the laboratory such as the resilient modulus (M_R) of the mixture (ratio of the repeated stress to the recoverable strain for repetitively applied loads), according to Shackel (38) are primarily dependent on the bitumen content of the foamed asphalt mixture. Thus, it appears that there may be an optimum or critical bitumen content at which the rate of accumulation of permanent deformation is a minimum and for which the M_R is a maximum.

CONOCO in a technical bulletin published in 1979 (17) stated that "...comparative data available through this time suggest potentially

significant differences in response between various hot mix and FOAMIX (foamed asphalt-aggregate mixture) combinations, under either constant or dynamic loadings". Since those tests were not specifically directed to such a study, no data were available to portray these differences in loading conditions on Poisson's ratio of the mixture. CONOCO assumed a Poisson ratio of foamed asphalt mixtures as being 0.1 based on related research studies held at the University of New South Wales. However, it is considered a conservative assumption since this parameter varies up to 0.4 or more. Nevertheless, research results were encouraging and they showed similar differences between hot mix and emulsion mix combinations as reported by the Asphalt Institute (R and D Progress, Vol. 8, No. 2, June 1979). "Such data appear to support the need for different criteria for design of foamed asphalt mixes as well as for emulsion mixtures than those used in hot mix design".

This same study (17) also shows that the foamed mixes are significantly less affected by changes in temperature than are conventionally produced mixtures. This difference in the behavior of foamed asphalt mixtures, again is attributed to the distribution of the asphalt in this process. In the case of foamed mixes, CONOCO explains, the asphalt is concentrated in the fines fraction and does not cover the larger aggregate particles as is the case with the hot mixed materials. Thus, greater mechanical interlock is developed since the coarse particles are free of a coating of bitumen and FOAMIX should be less affected by temperature conditions.

Effects of curing time in asphalt mixtures, generally are related with the degree of moisture evaporated from the mix. The retained moisture interacts with the foamed asphalt present and affects almost

all the strength and stability properties of the material. Liquids contained in the mix can be in larger or lesser amounts depending on the age (curing) of the mixture and the atmospheric conditions present in the environment where these mixtures are being cured. Also, the permeability of the mix (generally expressed in terms of percentage of air voids in the mixture), related with the degree of compaction, gradation, etc., will determine the amount of moisture absorbed by it when subjected to the action of the water.

Based on the experience gained from his experimental work, Shackel (38) reported that "...the performance of the stabilized material deteriorates noticeably once the degree of saturation (during the water saturation test), exceeded about 70% of the total air voids of the sample". However, he states that this deterioration is not to the degree shown by samples of untreated material. Further study showed that "...for a given quantity and grade of bitumen, the M_R of the stabilized materials attained maximum values at particular saturations within the range of about 50 to 70%...This suggests that ideally the compaction conditions should be chosen so that the material is compacted dry of the line of optimum and that measures should be taken to prevent the material becoming saturated in service". In an actual pavement, this can be achieved by providing a full width seal and good subsurface drainage. "In other words, the most efficient use of the foam bitumen as a stabilizing agent was achieved at low saturations", so concluded Shackel.

Effects of binder content were discussed by Acott (3) and Shackel (38). Both stated that the response parameters achieve a maximum at a

certain level of asphalt content. The effects of binder content upon the M_R were found to be different for the dry and saturated bituminous mixtures.

Analysis of the visco-elastic properties of the asphalt itself (38) demonstrated that higher penetration bitumens were usually less resilient (less "elastics"). In other words, the initial strain and the stiffness of the material expressed in terms of M_R are reduced with the increase in the binder penetration.

Test results that reflect the resistance to deformation showed that the foam stabilized specimens are more elastic than the hot mix samples. However, the hot mixtures generally had the better resistance to nonrevoerable (plastic) deformations.

The correlations found between parameters and variables measured generally represent the influence of the variables considered in the type of response being observed. Parameters that can be evaluated in the laboratory as well as in-situ should be considered whenever it is possible. Also, strength, durability, stability, etc. responses should be measured in a way that they could be correlated with normally specified limits for the different mix design procedures of bituminous stabilized mixtures.

Finally, based on laboratory experiments and field measurements conducted in Australia (12), South Africa (3), Colorado (2). Iowa (29), etc., the following environmental, applicational and economic advantages, foamed asphalt stabilized materials are reported to have:

- Roadway base courses can be effectively stabilized by this process. Foamed asphalt base and subbase construction is a viable alternate to plant mix bituminous base.

- This process is relatively simple and does not require major investments in new equipment. Standard equipment can be used in continuous plants, for insitu mixing, and in drum dryer mixers with minimum modification.

- Minimum pollution problems are obtained when foamed asphalt is used in asphalt recycling. Then process is ecologically desirable, because of the lower energy used in its production. The economical use of marginal aggregates is possible.

- Binder costs are not increased by dilutents and additional manufacturing costs. No dilutents as in outbacks, or water in emulsion, have to be hauled from the source to the mixing plant.

- No aeration or curing is required before compaction. The foamed asphalt mix can be compacted immediately after laydown, and can be quickly opened to light traffic.

- Cold mix base courses can be produced with cold, wet and marginal aggregates including sand and gravel.

- The mix can be stockpiled and placed at a later day. The mix is not subjected to leaching of the binder by rain.

- The mix, once placed can be reworked easily even after several days.

- Laboratory investigations as well as test results on field samples suggest that higher or the same strength and stability properties of the mix can be achieved with a lower binder content than conventional mixes.

These potential advantages for producing low cost pavement mixtures are reported for foamed asphalt mixtures under different types of test procedures, aggregates utilized, and environmental as well as

load conditions. However, based on these studies, it was also concluded that foamed asphalt mixtures do not appear suitable for high quality wearing courses, since the lack of coating of the larger aggregates would probably cause raveling of the surface (2). The design procedure for use of foamed asphalt has not been fully developed. The moisture susceptibility of the mixture should be carefully and realistically analyzed, since the durability of foamed asphalt mixes appears to be very low when subjected to severe weather.

EQUIPMENT AND MATERIALS

Equipment

The equipment used for the fabrication and testing of foamed asphalt mixtures is one of the major contributors for the quality of the finished samples and the accuracy of the test results.

The major equipment items used in this study were:

- Laboratory FoamixTM Asphalt Dispenser developed by the Continental Oil Company. This device primarily consists of a 2 gallon storage tank, control panel, and outlet nozzle.
- Hveem or California Kneading Compactor
- Diametral Resilient Modulus Device
- Hveem Stabilometer and Compression Machine
- Marshall Equipment
- Mechanical Mixer, Ovens, and other equipment.

Bituminous Material

A previous laboratory analysis (11) of the foaming characteristics of diverse types of asphalt cements from different sources concluded that the asphalt cement graded as AC-20, from Amoco Oil Company of Whiting, Indiana, was the most suitable for use in this study.

The foam characteristics of various asphalt cements at different temperatures and water contents added during the foaming process were compared. It was shown that in general, the AC-20 asphalt cement from this source had an expansion ratio greater than 12 times its original

volume of the foam to be reduced by 50% as long as 13 seconds, when foamed with 2% by asphalt flow of cold water and at a heating temperature of 325°F (160°C).

The properties of this asphalt cement are as follows:

TABLE 2. - Properties of Asphalt Cement AC-20.

Penetration, 100 gr., 5 sec., 77°F ¹ , (0.1mm)	42
Softening point, Ring and Ball ² , (°F).	118
Ductility of 77°F (25°C), 5 cm/min ³ , (cm)	150 ⁺
Kinematic Viscosity at 300°F (150°C) ⁴ , (cst)	229
Kinematic Viscosity at 325°F (160°C) ⁴ , (cst)	126
Kinematic Viscosity at 350°F (180°C) ⁴ , (cst)	72

Note:

- 1 ASTM D-5
- 2 ASTM D-36
- 3 ASTM D-113
- 4 ASTM D-2170

Pit Run Gravel

The first of the three different mineral aggregates used in this study was a mixture of sand and gravel better known in highway construction as pit-run gravel mineral aggregate.

Since throughout the state this designation is given to different combinations of sand and gravel, a thorough study was developed in order to determine a representative gradation or sieve size distribution of the aggregate particles, as well as other characteristics for a uniform and typical pit-run gravel aggregate.

As a result of this analysis, a blended mixture of sand and gravel, intended to have the most representative gradation of all the samples

examined, was recommended by ISHC personnel for use in this laboratory study,

TABLE 3. - Recommended Gradation for Pit Run Gravel Aggregate.

<u>Sieve Size</u>	<u>Percent Passing</u>	<u>Percent Retained</u>
1"	100	-
3/4"	90	10
1/2"	84	6
3/8"	76	8
#4	65	11
#8	50	15
#16	35	15
#30	20	15
#50	8	12
#100	5	3
#200	3	2
<200	-	3

Modified Class 5-D Base Mixture (Crushed Stone)

The second type of aggregate used in this study was a product resulting from the crushing of limestone bedrock with all fragments having faces resulting from fracture. It is commonly known as crushed stone aggregate. The material was dried, separated in sieve sizes, and then stored at the same manner as for the other two aggregates. The recommended gradation for the crushed stone is reported next.

TABLE 4. - Crushed Stone Recommended Gradation.

<u>Sieve Size</u>	<u>Percent Passing</u>	<u>Percent Retained</u>
1"	100.0	0.0
3/4"	96.7	3.3
1/2"	79.0	17.7

TABLE 4. (Continued)

<u>Sieve Size</u>	<u>Percent Passing</u>	<u>Percent Retained</u>
3/8"	66.0	13.0
#4	43.5	22.5
#8	34.0	9.5
#16	25.0	9.0
#30	17.1	7.9
#50	14.0	3.1
#100	11.5	2.5
#200	9.0	2.5
<200	-	9.0

Outwash Sand

The outwash sand designated for use in this study was obtained from a source located in the northwestern part of Indiana. The gradation of this sand is shown in Table 5.

TABLE 5. - Outwash Sand Recommended Gradation.

<u>Sieve Size</u>	<u>Percent Passing</u>	<u>Percent Retained</u>
3/4 in.	100	0
1/2 in.	99.7	0.3
3/8 in.	99.5	0.5
No. 4	97.6	2.4
No. 8	94.3	5.7
No. 16	90.7	9.3
No. 30	78.4	21.6
No. 50	38.3	61.7
No. 100	9.5	90.5
No. 200	2.4	97.6
Pan	0	100

DEVELOPMENT OF EXPERIMENTAL PROCEDURES

Mixing, Compaction and Curing Process

The process of choosing the right amounts of mixing water content and the foamed asphalt quantities needed for compaction required trial mixes composed of different combinations of these two variables.

- Mixing Water. - First, the optimum moisture content for mixing purposes was determined at room temperature. The review of the literature shows that optimum mixing conditions occur when the soil or aggregate was brought to its maximum volume consistent with easy manipulation (12, 35). This stage of maximum volume is called the "fluff point" moisture content of a defined soil or aggregate type. However, these quantities of initial moisture added to the mix, may or may not be, the optimum water content as determined by observations and measurements made based on the density, stability, strength, and other parameters of the compacted mixture. Adjustments of the initial moisture added are frequently required for the determination of the optimum moisture content; the fluff point can be used as the initial amount required in the preparation of trial mixes. This amount of water was found to be 3.9%* (6% by minus No. 4 sieve fraction) for the pit run gravel, 5.0%* for the crushed stone (11.5% of minus No. 4 fraction), and 6% for the outwash sand material.

* Based on total dry aggregate weight.

The aim of these preliminary analyses of the mixture behavior was the determination of two of the most important variables involved in this study: the initial moisture content of the aggregate before mixing as well as the amount of foamed asphalt that should be added to the different mixtures.

- Foamed Asphalt Content. - The fluff point moisture content for both of the aggregates was used with trial foamed asphalt contents recommended by CONOCO's proposed mix design for foamed asphalt mixtures. A trial of 3.5% of foamed asphalt content by dry aggregate weight was recommended for materials having more than 50% of minus No. 4 sieve fraction and 3.0 to 5.0% of passing No. 200 mesh, as for the pit-run gravel material. On the other hand, for materials with less than 50% of minus No. 4 mesh fraction and 7.5 to 10.0% of passing No. 200 sieve (crushed stone), 4.0% of foamed asphalt addition was reported as being adequate.

Several sets of specimens (three per set), were mixed with less and greater amounts of foamed asphalt than recommended above.

The optimum amount of moisture content (3.9%*), was added to the mixture of pit-run gravel. Five different foamed asphalt contents were mixed and compacted in the kneading compactor giving five different sets of specimens. The samples then were left for three days curing at room temperature, and then the unit weight of the specimens was determined by means of the Bulk Specific Gravity Test of Compacted Bituminous Mixtures using Saturated Surface Dry Specimens according to the ASTM #2726 standard procedures.

* Based on total dry aggregate weight.

As an example, Figure 1 shows the test results for pit run gravel mixtures obtained at the fluff point moisture content with five different amounts of foamed asphalt content and cured for three days.

The results obtained for mixtures made with crushed stone at 5% moisture added and four different foamed asphalt contents, are graphically reported in Figure 2.

A common testing and mixing temperature of 72°F (22°C) was used in the process for both mixtures. This analysis indicated that for pit run gravel mixtures, lower amounts of foamed asphalt are necessary to achieving maximum density than for crushed stone mixes. Mixtures containing 3.25 and 4.00% of foamed asphalt for pit run gravel, and 4.0 and 4.5% of foamed asphalt for crushed stone mixtures were tried. The degree of dispersion of these amounts of foamed asphalt in mixtures containing different quantities of mixing water was analyzed. Partially mixed foamed asphalt was observed when both of the mixtures have mixing water with less or excessive amounts than the fluff point initial moisture content.

A study conducted on the pit run gravel along, showed that mixtures containing less water than 4% by minus No. 4 sieve fraction (2.6% by total dry aggregate weight), have a partially mixed appearance with 50 to 70% of bitumen in small balls or particles. Thus, less amounts of mixing water would simply lead to worse mixing conditions with mixtures containing more free bitumen and fewer aggregate particles coated.

Mixtures of foamed asphalt and crushed stone gave the same observations. The least amount of mixing water for obtaining an adequate mixture was found to be about 3.5% by total weight of dry

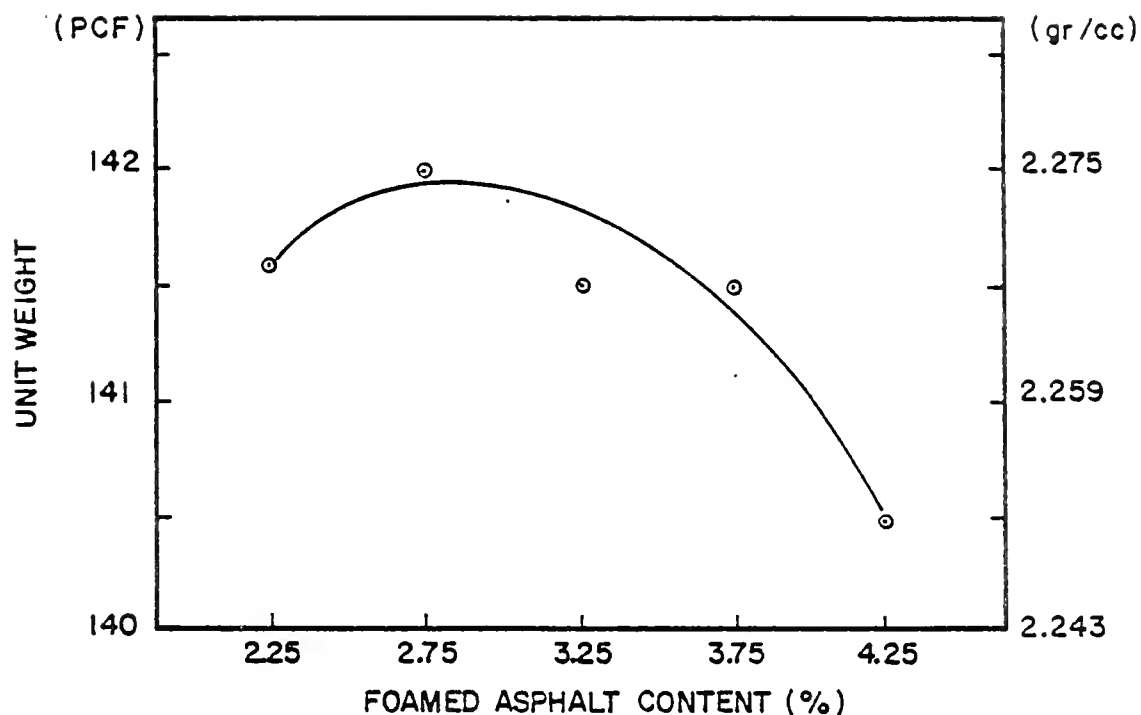


FIGURE 1 , UNIT WEIGHT FOR PIT RUN GRAVEL MIXTURES AT DIFFERENT FOAMED ASPHALT CONTENT, 3.9 % INITIAL MOISTURE ADDED (FLUFF POINT), AND THREE DAYS CURING.

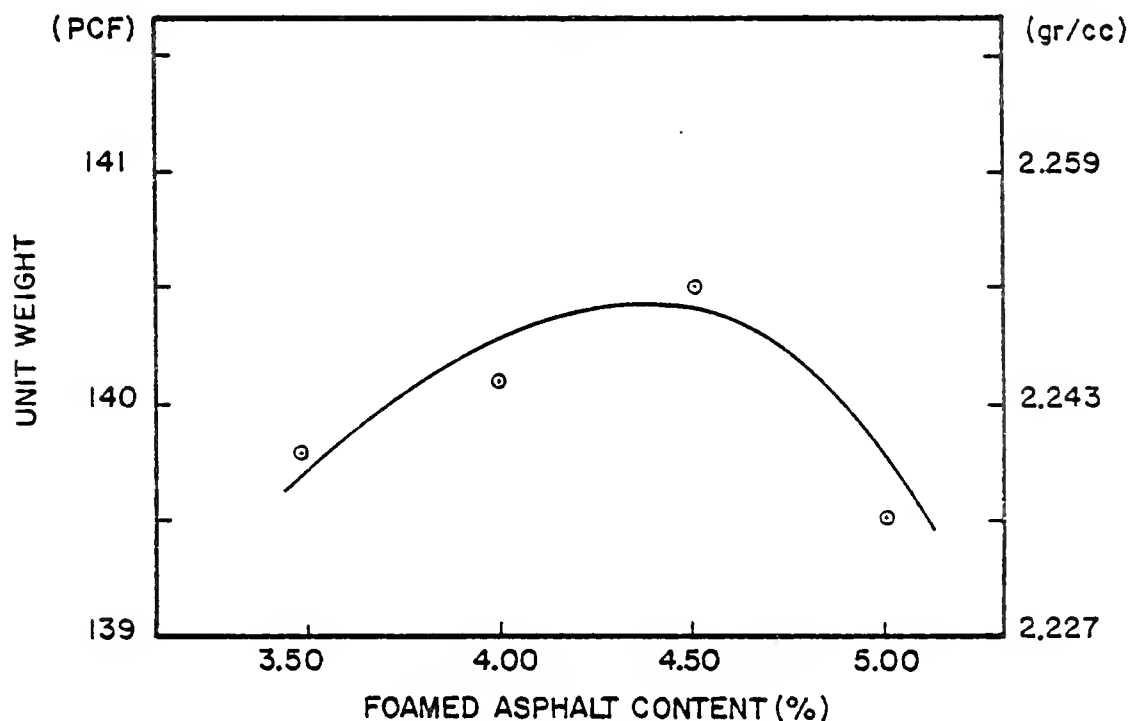


FIGURE 2 , UNIT WEIGHT FOR CRUSHED STONE MIXTURES AT DIFFERENT FOAMED ASPHALT CONTENT, 5.0% INITIAL MOISTURE ADDED (FLUFF POINT), AND THREE DAYS CURING.

aggregate. Final values of foamed asphalt content and initial mixing water to be added, were to be obtained after observations performed during the mixing and the compaction processes.

These observations led to the following remarks:

- Mixtures made of pit run gravel with 3.25 and 4.00% of foamed asphalt, at 2.6% of initial moisture added, presented the minimum acceptable mixing appearance and compacted relatively well. The same was true for mixtures of crushed stone with 4.0 and 4.5% of foamed asphalt content at 3.5% by dry aggregate weight of mixing water added.

- Mixes of pit run gravel prepared with these two levels of foamed asphalt (3.25 and 4.00%) and water contents as high as 5.2% by total dry aggregate weight (8% by minus No. 4 fraction) gave a good appearance during mixing. Free bitumen started to group into small balls in the mixture for levels of moisture above this.

- Excessive water seeped from the mold, for values of initial moisture added higher than 5.2% when compacting the specimen.

- Completely dispersed bitumen was observed when mixed at the fluff point of 3.9% moisture content. Hands were left clean when the mixture was handled.

- Balls of free bitumen were first observed in crushed stone mixture when amounts of mixing water exceed 4.5% by total aggregate weight.

Mixtures prepared of this material at both levels of foamed asphalt content with moisture at the fluff point of 5%, led to an excessive bleeding of water, and a significant instability of the mixture. The compaction was achieved with difficulty and frequently the

upper surface of the specimen where the foot pressure was applied, was not as smooth and even as for specimens made of mixes with less initial water in them.

The use of this method of compaction for crushed stone-foamed asphalt mixtures containing 5.0% initial mixing water and 4.0 and 4.5% of foamed bitumen, caused some excess water together with some fines to be forced out of the mold during compaction. This was an indication that 5.0% of initial mixing water would be more than the optimum amount required for this type of mixture especially when using this method of specimen preparation, and when the foamed asphalt content was as high as 4.5%.

- Compaction and Coating. - Despite the findings that the use of the unheated foot of the kneading compactor, was not suitable for preparing cold-mixes into specimens (43), no significant disturbances were observed during the process of mixtures utilized in this laboratory study. It is believed that the low bitumen contents of these mixtures were the main reason for the material not sticking to the foot of the kneading compactor.

Ranges for initial moisture added of 2.6 to 5.2% by total dry aggregate weight for pit run gravel mixtures, and 3.5 to 4.5% for mixes made of crushed stone, were next analyzed.

The upper limits of this percentage range (5.2 and 4.5% of initial moisture respectively) were determined mainly by analyzing the stability of the mixture during the compaction process as well as the dispersion of the foamed asphalt during mixing activities.

These ranges of initial moisture were the best operable amounts of mixing water for these type of mixtures when prepared at their

respective amounts of foamed asphalt. Also, it is generally assured that wet and untreated aggregates in the field contain amounts of moisture that range from 4 to 5% of water on their surface (9). Therefore, it was found that there was no need to use more mixing water than the quantities reported as being the upper limits of the most suitable range determined before (5.2 and 4.5% of mixing water respectively), nor to cure the mixed material for any reduction in moisture prior to compaction. Thus, time and energy are saved by preparing the specimens at room temperature and at whatever moisture content they have at the moment of compaction.

The foamed asphalt process offers a way of incorporating bitumen into wet, cold materials without prior processing. No aeration of the mix at the site is required before compaction and no emission of hydrocarbons will result afterward. As a result, there are fewer constraints from the weather with regard to the use of this agent in the field.

The mid point of the range of mixing water, 3.9% (fluff point) for the pit run gravel and 4.0% for the crushed stone, gave the most desirable conditions for operations during the mixing and compaction of the mixtures, as well as good appearing specimens.

The degree of coating the cold wet aggregate particles by the foamed asphalt was determined during and after the mixing process. The added bitumen was concentrated in the fines of the mix, leaving the large particles relatively uncoated. The ranges of mixing water mentioned before, gave the best rate of foamed asphalt dispersion in the mix. The hands were left clean when the mixture was compacted manually

into round chunks. When these balls of mixture were divided into two pieces, they did so, with a clean and clear break throughout the mass.

Some coating of the coarse aggregate was obtained when the mixture was blended and mixed by hand with the plus No. 4 sieve fraction for half a minute. These overall degrees of coating were considered adequate and no further means to improve it were explored. The stability of the mix when placed, will depend mostly on adequate compaction, which in turn will depend on having the proper amount of moisture in the mix so compaction can be achieved.

- Mixing Temperatures. - Although different mixing temperatures were used in the study, these different levels of temperature are mainly intended to resemble the environmental effect that would take place in the mixing process when aggregates are mixed with foamed asphalt during the fall or spring at temperatures of 50°F (10°C), or during a hot sunny day of 100°F (38°C) including the normal temperature of 72°F (22°C).

- Curing. - A final observation made during this early stage of the experiment was that specimens of both mixes at any level of moisture and foamed asphalt contents (within their respective ranges), were extremely weak to be extruded from the mold after being mechanically compacted. For this reason, the specimens were allowed to cure for one day and then extruded from the mold, throughout the entire study.

While compacting a set of specimens (three out of the same batch), care was taken to avoid any effect due to the fact that the operation of compacting three specimens take approximately 45 minutes to one hour

to be completed. The pans containing the mixtures waiting to be compacted, were covered with a wet cloth to avoid any loss of moisture and the different specimens compacted for the different batches were labeled in a discriminatory way, for future testing purposes in order to randomize any effect that could occur for being compacted first or last, in the order of the same set of specimens. Also, possible changes and their respective effects in the mix behavior, of room humidity and temperature levels were randomized by preparing specimens during the same day of operation for testing them, for example at one day of curing, and the same asphalt or mixing water contents.

As a highlight summary of this section, it can be stated that the main findings from this preliminary phase of the study, were the determination of the levels of foamed asphalt and mixing water contents to be used with the respective aggregates intended to lead to good and representative mixtures of this material, by means of the foamed asphalt stabilization process for base and subbase aggregates. Table 6 summarizes these findings.

TABLE 6. - Levels of Fluid Contents Used in the Study.

<u>Aggregate Type</u>	<u>Foamed Asphalt*</u>	<u>Mixing Water*</u>
Pit Run Gravel	3.25 and 4.0%	2.6, 3.9, and 5.2%
Crushed Stone	4.00 and 4.5%	3.5, 4.0, and 4.5%
Outwash Sand	3.25 and 4.25%	3.5, 4.75 and 6.0%

*Note: Percentages by total dry aggregate weight.

Inspection of Foamed Asphalt Mixtures. - The difference in the degree of coating and percentage of coated aggregates for foamed asphalt mixtures made from these three types of mineral aggregate, was

evaluated by means of the ASTM D-2489 (Degree of Particle Coating of Bituminous-Aggregate Mixtures) standard procedures. Although no substantial coating of the large particles was achieved as concluded from this examination, it is generally accepted that the energy provided in the field during the preparation of the mix produces a better coating of the coarse fraction than was obtained in the laboratory using a completely cold procedure (18).

A summary of all factors considered in the mixing and preparation process of all mixtures used in this study is presented in Table 7.

Mix Design Variables

The main concern of this study was to analyze the suitability of cold-mix foamed asphalt mixtures as a stabilized base or subbase course for pavements. The variables measured were intended to give indications of the quality of performance of these mixtures, as well as an aid in the development of design procedures for the implementation of the relatively new concept of the use of foamed asphalt as a stabilizing agent for Indiana base and subbase materials. Stabilization is a process wherein the behavior properties of the material are improved for its intended use. Many laboratory and field studies have shown that successful stabilization is produced with design and construction techniques that properly consider the factors that affect the performance of an asphalt mix. Robnett and Thompson (1969) p. C-24; among others, indicates that the design of a bitumen-stabilization mix will involve several variables, each of which can have a different interaction effect with the other variables. Therefore, the parameters under investigation in this study, and listed next, are believed to be important factors that will affect the properties of a foamed asphalt mix.

TABLE 7. - Specimen Handling and Preparation. Summary of Factors Considered.

FACTOR		
AGGREGATE TYPE	PIT RUN GRAVEL	OUTWASH SAND
		MODIFIED CLASS 5-D (CRUSHED STONE)
FOAMED ASPHALT CONTENT (1)	3.25% and 4.00%	3.25% and 4.25%
		4.00% and 4.50%
MIXING WATER CONTENT (1)	2.6, 3.9, and 5.2%	3.5, 4.75 and 6%
		3.5, 4.0, and 4.5%
MIXING TEMPERATURE (2)		50°F, 72°F, and 100°F
COMPACTION METHOD		HVEEM KNEADING COMPACTOR
CURING TIMES (3)		1, 3, and 7 DAYS

NOTE: (1) - Percentages by total weight of dry aggregate.

(2) - 50°F = 10°C
 72°F = 22°C
 100°F = 38°C

(3) - All specimens cured at room temperature; approx. 72°F (22°C).

Aggregate Type. - Three different types of aggregate commonly used as base and subbase course materials in the state of Indiana, were included in the study; namely, Pit Run Gravel, Modified Class 5-D Base Mixture (Crushed Stone), and Outwash Sand.

Research has shown that aggregate gradation is an important variable in producing a quality result. Rice and Goetz (1949) showed that the presence of angular fines in the correct quantity will create much greater strengths in the resulting mixture than if the fines are absent. For this reason, the advice and guidance of Materials and Test, personnel of ISHC was requested to establish the appropriate gradation of these three materials, as listed before in this report.

Type of Binder Material. - After the completion of an analysis of for foaming characteristics of various asphalt cements obtained from different sources, and generally used in the State of Indiana for bituminous construction (11), one type of binder material (Asphalt Cement grade AC-20) was chosen for use in the preparation of all the foamed asphalt mixtures.

Levels of Added Foamed Asphalt (%FA). - In bituminous stabilization, the binder has the role of: a) giving strength to the granular materials by providing a binder at low confining pressures in service; b) stabilizing the moisture of relative low plasticity cohesive material (pit run gravel); and c) providing some waterproofing effects. The amount of bitumen required depends on the property one wishes to optimize, e.g. strength or waterproofing. For Indiana, it would appear that strength and stability, free swell and permeability, and durability relative to wetting-drying and freezing-thawing will be factors that

need to be evaluated with regard to the successful use of foamed asphalt in the state.

This study will concentrate on the strength and stability of the mixture. The use of low binder contents as well as high void contents on the mix gives rise to some concern. Thus, the durability characteristics of foamed asphalt mixtures will be determined in a separate laboratory analysis performed by other investigators.

Two levels of foamed asphalt content per type of aggregate were selected after some trial mixes with different amounts of bitumen. The percent of foamed asphalt added (%FA) is expressed as the percent by weight of total dry aggregate in the mixture.

Amounts of initial moisture added (%W). - Percentages of moisture added, are the amounts of water initially introduced to the aggregate just before mixing with the respective quantity of foamed asphalt for the batch, and are expressed as percent by weight of total dry aggregate in the mix.

The amount of water present in the aggregate (initial moisture added), is a factor in determining the ease of dispersion of the bitumen. Moisture also plays a role in determining the magnitude of the compacted density of the mix that will be produced by a given subsequent compaction. As a result of the trade-offs that have been made in order to establish the appropriate liquid content in the mix for having the best dispersion of bitumen, and the highest compacted densities of the samples among other characteristics, three different mixing water contents were chosen to be used with each of the aggregate types involved in this study.

Curing times. - Three curing times at room temperature were used. They are 1 day, 3 days, and 7 days. Curing time is the time allowed for a specimen to gain strength between the time of compaction and the time of testing. In other words, it is the time in the field between the compaction of the mechanically laided down mixture and the application of any traffic load or environmental effect that would subject the mix to any type of stress.

Curing time of one day were expected to reproduce by means of laboratory tests, the ability, if any, of the mixture prepared as a base or subbase course, to quickly permit the hauling traffic needed on the construction work, and the resistance of the mix to severe weather situations such as a heavy rainfall. Specimens tested after this curing time period (1 day), would show the strength gained by the mixture at that time and the percentage of this strength retained after exposure to water deterioration by means of the water sensitivity test are described later in this report.

Tests performed in samples of three and seven days cured at room temperatures would show the increment, if any, in the gained strength and stability of the mixtures. The seven days curing limit was chosen because it was expected that the excessive moisture that contributes to the instability of the mixtures would be almost totally eliminated from the mix. The relatively total strength of the sample was reached in this period of time.

Compaction method. - The preparation of realistic test specimens is essential to the correlation of laboratory and field properties of bituminous mixtures. Hveem's method of fabricating asphalt concrete

specimens employs the mechanical kneading compactor developed by the Triaxial Institute, and this compactor was selected to prepare the samples used in this entire laboratory analysis. Although specimens can be prepared by other means such as the Gyratory Shear Method or the Marshall compactor this method was preferred and considered more practical for the purposes of this study. The basic principle of this compactor is to mold a laboratory specimen possessing the density and stability corresponding to a pavement after one year of service (19).

Mixing and Testing Temperatures. - Two testing temperatures (FT), as well as three different mixing temperature (FM), were selected in order to represent the environmental effects of the weather temperature on the mixture behavior during the mixing and the testing of the specimens.

Table 8, Table 9 and Table 10 summarize the various factors considered in this laboratory study for each type of mixture utilized.

Testing Procedures

The following section is a brief description of the principal test procedures as well as test conditions that were considered in this laboratory study. It is assumed that the specimens are already mixed, compacted and cured at this stage of the work.

These specimens have been made of three different aggregate types with their respective foamed asphalt and initial mixing water contents, and mixed at three different temperature conditions. All of the samples were compacted in the Hveem kneading compactor. These samples have also been cured at room conditions for one, three or seven days, respectively. Specimens that are to be tested after three or seven

TABLE 8 , SUMMARY OF THE EXPERIMENTAL VARIABLES USED FOR PIT RUN GRAVEL - FOAMED ASPHALT MIXTURES.

TABLE 8 , SUMMARY OF THE EXPERIMENTAL VARIABLES USED FOR PIT RUN GRAVEL - FOAMED ASPHALT MIXTURES.													
AGGREGATE TESTING TEMPERATURE FOAMED ASPHALT CONTENT (%) INITIAL MOISTURE ADDED (%) MIXING TEMPERATURE (°F) CURING TIME		PIT RUN GRAVEL											
		50°F (10°C)						72°F (22°C)					
		3.25%			4.00%			3.25%			4.00%		
		2.6	3.9	5.2	2.6	3.9	5.2	2.6	3.9	5.2	2.6	3.9	5.2
1 DAY	50	3**	3	3	3	3	3	3	3	3	3	3	3
	72	3	3*	3	3	3*	3	3	3*	3	3	3*	3
	100	0	0	0	0	0	0	0	0	0	0	0	0
3 DAYS	50	3	3	3	3	3	3	3	3	3	3	3	3
	72	3	3*	3	3	3*	3	3	3*	3	3	3*	3
	100	0	3*	0	0	3*	0	0	3*	0	0	3*	0
7 DAYS	50	3	3	3	3	3	3	3	3	3	3	3	3
	72	3	3*	3	3	3*	3	3	3*	3	3	3*	3
	100	0	0	0	0	0	0	0	0	0	0	0	0

NOTE: * HVEEM STABILOMETER TEST PERFORMED IN MR TESTED SPECIMENS

****** NUMBER INDICATES THE NUMBER OF REPLICATES PER CELL

(1) PERCENTAGE BASED ON TOTAL DRY AGGREGATE IN THE MIX

TABLE 9 , SUMMARY OF THE EXPERIMENTAL VARIABLES USED FOR MODIFIED CLASS 5-D BASE MIXTURES (CRUSHED STONE) - FOAMED ASPHALT MIXES.

AGGREGATE		MODIFIED CLASS 5-D BASE MIXTURE (CRUSHED STONE)									
		50°F (10°C)					72°F (22°C)				
		4.00%		4.50%			4.00%		4.50%		
TESTING TEMPERATURE	FOAMED ASPHALT CONTENT (I)	3.5	4.0	4.5	3.5	4.0	4.5	3.5	4.0	4.5	4.5
INITIAL MOISTURE ADDED (%) (I)	MIXING TEMPERATURE (°F)	50	72	100	50	72	100	50	72	100	50
CURING TIME	1 DAY	3**	3	3	3	3	3	3	3	3	3
	3 DAYS	3	3*	3	3	3*	3	3	3*	3	3
	7 DAYS	3	3*	3	3	3*	3	3	3*	3	3

NOTE: * HVEEM STABILOMETER TEST PERFORMED IN MR TESTED SPECIMENS

**NUMBER INDICATES THE NUMBER OF REPLICATES PER CELL

(I) PERCENTAGE BASED ON TOTAL DRY AGGREGATE IN THE MIX.

Note 72°F Mixing , 72°F Testing

*Number indicates the replicates per cell

Curing Period	Percent Moisture	Bitumen Content (%)		
		3.25	4.25	5.5
1 DAY	3.5	3 *	3	2
	4.75	3	3	2
	6.0	3	3	2
3 DAYS	3.5	3	3	2
	4.75	3	3	2
	6.0	3	3	2
7 DAYS	3.5	3	3	
	4.75	3	3	
	6.0	3	3	

TABLE 10 , EXPERIMENTAL DESIGN FOR OUTWASH SAND-FOAMED ASPHALT MIXES.

days of curing, were extruded from the molds one day following compaction. This period of time permitted the specimens to gain some strength in order to be more easily handled and avoid any damage that could happen during the extrusion process. On the other hand, specimens tested after one day of curing, were extruded one to two hours prior to the completion of this period of time in order to permit different measurements such as, the moisture lost while the sample was curing in the mold, the height of the specimen, etc. Also, it was necessary to allow the specimen temperature to be lowered to the required testing temperature.

Testing Temperature Control._

The same temperature controlled chamber used for cooling the aggregates prior to mixing them, was utilized to obtain the required test temperatures of 50°F (10°C). These test temperatures were chosen to be 50°F (10°C) and 72°F (22°C) in order to reflect the significance of the increment, if any, on the stiffness of the mixture when tested at temperatures lower than normal conditions. For normal testing temperatures (72°F), the specimens were left at room conditions and tested without prior special care other than the ones existing to control the laboratory room environment.

A thermometer buried inside a dummy specimen was used to indicate the actual temperatures of the test samples inside the chamber when the required test temperature was 50°F (10°C). It took approximately one hour or less to lower the sample temperature for this test condition. Because of the extra amount of time required before the test itself could be started, specimens for this set of conditions were placed

inside the chamber to complete the last hour of their curing time while being cooled.

All tests were performed on specimens subjected at these two temperature conditions, 50°F and 72°F (10°C and 22°C), and the results obtained for these different temperature levels which reflect the outcome of these experiments are presented in this report.

Density of Compacted Specimens.--

The unit weight at time of compaction, which is a measure of the compactibility of the foamed asphalt mixture during the field construction, is a useful parameter in the mix evaluation. High unit weights achieved during construction are recommended in order to reduce further compaction by traffic that leads to rutting of the pavement. On the other hand, a certain amount of air voids in the mixture is needed to increase drainage and curing rate (4). In this study, two procedures were followed to obtain an indication of the degree of compaction and the compactibility of the mix.

First, the bulk specific gravity of the sample was obtained by the Saturated Surface Dry Method, ASTM D-2726; however, since foamed asphalt mixtures have higher air voids content than normal hot mix materials, the absorption of moisture during this process was significant (from one to one and a half percent of the total weight of the specimen), therefore distress occurred weakening the specimen and distorting further test results. For these reasons the bulk specific gravity of the sample was determined on specimens prepared for this objective only. Air void contents and unit weights were calculated from the results obtained by these standard procedures. Specimens utilized in this test procedure were discarded and not used in further testing.

The degree of compaction of each prepared sample was to be determined. By reasons explained previously, it was quite difficult to obtain. Consequently, a second and more convenient way to obtain this information was pursued. After the samples were cured, their weights in air and their heights were measured and recorded. The weights were measured with a precision of ± 0.5 gr. and the heights were recorded with precisions up to ± 0.01 in. (± 0.3 mm). The volume and unit weight of the samples were calculated and the degree of compactibility of the mixture was attained without damaging the samples which were used later in test procedures as described next.

Resilient Modulus Test Procedure

One of the common dynamic tests frequently used to determine the resilient characteristics of the pavement material mixtures is the method of diametral loading. The procedure in this study to measure the resilient modulus (M_R) is outlined as follows:

1. - The weight in air and the height of the specimen was determined for the further calculation of the degree of compaction of the sample as well as the retained moisture content among other properties.
2. - The specimen temperature was adjusted to its required level (50 or 72°F) by the procedures explained before (testing temperature control). The sample was centered between the two loading strips of the loading frame of the equipment as follows: the most upper strip rests on top of the specimen, applying a light touch of the loading head of the piston.
3. - Care was taken to make sure that the specimen was exactly centered between the two loading strips by means of specially designed rectangular rules.

4. - The auxiliary equipment such as the chart recorder, voltmeter, and LVDTs should be previously turned on for a period of half an hour before the test is initiated. This step is very important in order to avoid distorted test results between the first and last specimen tested, principally when the number of samples to be tested is large. After this initial period of time, the LVDTs must be calibrated by means of a micrometer for the different scales of the chart recorder.

5. - After the equipment is calibrated and the specimen placed in the right position, a pulsating load of 50 pounds (220 N) was applied across the vertical diameter of the specimen every three seconds with a duration of 0.1 seconds.

6. - The load applications cause changes in the output voltages of the LVDTs which were converted to movements of the recording pens. The sensitivities of the recorder channels and the positions of the pens were adjusted to obtain recordings within the chart (see Figure 3 for typical readouts). The speed of the chart movement was adjusted to 5 mm/sec (0.2 in/sec.).

7. - The pulsating load was applied several times to the specimen before the results were considered. One and a half minute of pulsating load application was imposed on specimens cured at 3 or 7 days. For specimens of only one day of curing, or water saturated (all levels of curing time), one minute of this pulsating load application was allowed. All these conditions were the same applied for specimens at both levels of testing temperature, however this was not fulfilled in all cases, especially at low curing levels and/or water saturated conditions because of the tension cracks that were formed in the specimens.

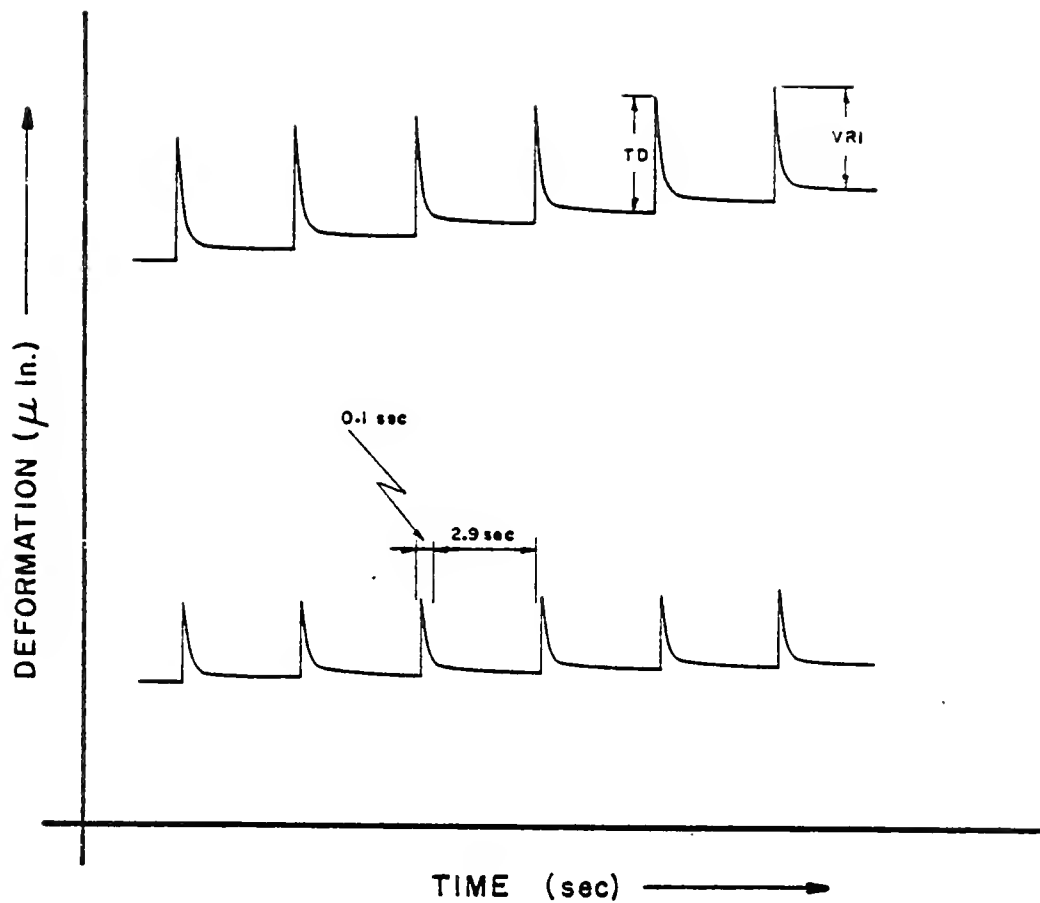


FIGURE 3 , TYPICAL CHART READOUT IN THE RESILIENT MODULUS TEST (MR).
(VERTICAL DEFORMATION VERSUS TIME).

NOTE: VRI = INSTANTANEOUS RESILIENT VERTICAL DEFORMATION (μ in.)

TD = TOTAL VERTICAL DEFORMATION (μ in.)

CHART SPEED = 0.2 in/sec (5 mm/sec)

8. - The specimen was rotated 90° and tested again in the new position using the same techniques mentioned previously. If large differences were found between deformation values for the two positions, the specimen was tested at a third position and the unreasonable results were discarded.

9. - After the test was completed, generally the same specimen was tested again in the Hveem stabilometer, except in cases where failure or cracks was noticed. In that case the samples were crushed into small pieces and dried in a forced draft oven for 24 hours at 230°F (110°C). The weight of the dry material (dry aggregate and asphalt cement) was determined and used later to calculate the dry unit weight and the moisture retained in the specimen as reported in the appendices with other test results.

A number of specimens were tested in the Hveem stabilometer after having been subjected to the resilient modulus procedures. This was possible due to the advantage that the resilient modulus test presents, namely that it is a nondestructive type of test. However, not all Hveem Stabilometer test results were obtained from specimens previously tested in the resilient modulus apparatus as explained below.

Hveem Stabilometer Test Procedure

Since the state of Indiana makes use of the Hveem test in the design of asphalt mixtures, it was decided that the foamed asphalt mixtures should be characterized using the Hveem procedure. A common way to do this, is to determine the Resistance R-value and a modified Hveem Stability S-value, at room temperature (30, 42). The resistance R-value test has been standardized by ASTM Designation D-2844, Resistance R-value and Expansion Pressure of Compacted Soils, which is

used for both treated and untreated soils or aggregates as well as in the design criteria for stabilized base materials. The conventional Hveem stability test is standardized by ASTM Designation D1560, Resistance to Deformation and Cohesion of Bituminous Mixtures by Means of Hveem Apparatus.

In this study, both the resistance R-values and the modified stability S-values were determined for the foamed asphalt mixtures at room temperature and at 50°F (10°C), rather than at 140°F (60°C) as required in the ASTM standard. As stated previously, since the R-value is used in the design criteria for stabilized base materials (7), it is thus an appropriate variable to be studied. The S-value is generally used in the design criteria for hot-mix surface course, but was calculated for comparison purposes and principally because both parameters were determined from the same test results. It was found that the value D_2 , the displacement value used in the calculation for both the R-value and the S-value did not change at repeated testing. D_2 is a function mainly of the surface texture of the specimen (30). It is thus appropriate to test a specimen in the stabilometer up to a load of 6000 lbs (26.69 kN) according to the standard Hveem stabilometer testing procedure, and to calculate the R-value as well as the S-value from the obtained data.

The following is a brief description of the testing procedures adopted in this study for specimens tested first in the Hveem stabilometer.

1. - Height and weight in air of the samples were determined before the test was performed.

2. - The specimens were tested in the stabilometer in accordance with the procedures of ASTM D1560. However, the test was performed at 72°F (22°C) and 50°F (10°C) temperatures, rather than at 140°F (60°C) as required in the ASTM standard.

3. - After being tested in the stabilometer, all of the specimens were tested in the Marshall apparatus, then crushed and kept in the oven at 230°F (110°C) for 24 hours.

4. - The weight of the specimen was taken before and after the 24 hours' oven drying. The loss of weight was used to determine the amount of retained moisture in the specimen.

Modifications of the above procedure were made for some experimental variations. After step 2 above was completed, the specimen tested at 50°F (10°C) was left in the temperature controlled chamber for at least one more hour before being tested in the Marshall apparatus, thus allowing the specimen to regain the required test temperature.

Specimens to be further tested in the Hveem stabilometer after being submitted to the resilient modulus test were kept one hour or less in the temperature chamber if such was the case. As in all the cases where 50°F (10°C) specimens test temperatures were required, a thermometer buried in a dummy specimen was used to control the time required for the samples to achieve this temperature.

Marshall Test Procedures

As pointed out before, this test was performed on samples already evaluated in the Hveem stabilometer and/or the resilient modulus apparatus. The objective for running this test, was to provide results

for comparison purposes within the samples analyzed in this laboratory work, and not for correlation with accepted Marshall values already listed in the existing bibliography.

The Marshall Stability (P) and Flow (F) test were performed as follows:

a) After completion of the Hveem stabilometer test, the specimens tested at 50°F (10°C) were kept the required amount of time in the temperature chamber, and then placed in the semi-circular testing head device of the Marshall apparatus. Specimens tested at room temperature were subjected to Marshall test without any temperature adjustment.

b) The testing load was applied to the sample through the testing heads, at a constant rate of deformation of 2 inches (51 mm) per minute, until failure occurs. The point of failure and the maximum deformation that occurs were recorded in a load-deformation trace made by an autographic recorder.

c) The specimen then was crushed and kept in the oven at 230°F (110°C).

Water Sensitivity Test Procedure

The water sensitivity test was used to measure the resistance of the foamed asphalt mixture to water. The method recommended in a recent laboratory report from the Asphalt Institute (8) was modified and used. The procedures that were followed in the study are briefly summarized below:

1. After the samples were cured, their heights and weights in air were measured.
2. The specimens were left for one hour in a vacuum at 30 mm Hg.

3. At the end of this period, distilled water at room temperature of 72°F (22°C) was slowly drawn into the bottom of the vacuum chamber until the samples were submerged at least a half inch below the surface.

4. The vacuum was then released and the specimens left to soak for 24 hours before testing.

5. Prior to testing (resilient modulus and/or Hveem stabilometer) the saturated surface dry weight of the specimen was determined in order to calculate the percentage of water absorption.

Not all the experimental factors were involved in the water sensitivity study. Tables presented in the Appendix of this report summarize the factors considered in the preparation of specimens for this test.

TEST RESULTS AND DISCUSSION

This section covers the laboratory testing that was used to analyze foamed asphalt mixes. The emphasis of this study is directed toward the development of a mix-design procedure for the use of foamed asphalt as a binding agent.

Specimens were compacted at various initial conditions in an effort to determine the effects of different variables on foamed mix strength characteristics. As the laboratory study progressed, knowledge and insight into foamed mix characteristics made it possible to reduce the program from a full factorial design. For any given set of conditions, at least 3 specimens were tested so as to arrive at an average value.

The experiment evaluated the foamed mix strength of both cured specimens and saturated specimens. The strength properties of cured specimens were measured by: Hveem resistance, modified Hveem stability, modified Marshall stability, and resilient modulus. The saturated specimens, resulting from vacuum saturation during the moisture sensitivity test, were tested for Hveem resistance and modified Marshall stability.

Mixing and Coating. - Foamed asphalt was observed to have very good mixing properties with the outwash sand. Although mixing seemingly became more difficult as moisture and bitumen contents increased, no problems such as stickiness or lumping were encountered. The foamed

specimens could be described as having a homogeneously, black speckled appearance. Present theory, which suggests that foamed bitumen selectively coats the smaller particles, appears to be valid and responsible for this speckled coating. An increase in bitumen simply produced darker samples with the same partial coating.

Compaction. - The foamed mixes became easier to compact as the amounts of moisture and bitumen were increased. It appears that a total fluid content (% moisture + % bitumen) near the soil's optimum moisture content, as determined by ASTM D698, produces the best compactive conditions. At the lower total fluid contents (3.5% moisture + 3.25% bitumen) there was a tendency for the kneading compactor to displace the mix during its downward stroke. This was especially evident during the early stages of compaction as the mix was often pushed over the sides of the mold. As the compaction process continued, this displacement stopped and specimens were compacted nicely. In general, compaction was not a problem for any of the moisture-bitumen combinations used in this study. It should also be noted that an attempt was made to produce a plot of dry density versus total fluid content, however, the data was very erratic and showed no particular trend.

Specimens compacted at 6% moisture, the highest moisture content used in this study, had a glossy moist look following compaction. It was then noted that the ensuing leveling process pushed small quantities of water from these specimens. Moistures above this 6% level probably require pre-compaction curing of the mix.

The Effects of Bitumen Content on Foamed Mix Strength. - The graphs shown in these sections were selected from a multitude of graphs, and are considered to be typical and representative. One particular set of

conditions (72°F mixing, 72°F testing, 6.0% moisture) is completely followed through the testing sequence, so the graphs may be viewed from a "total" mix design standpoint. Specimens cured for 3 or 7 day periods generally produce the most realistic and consistent data. Early test results revealed that 3 day R-values were nearly as good as the 7 day cured strengths. For this reason fewer 7 day cured specimens were produced, and the 3 day strength data was primarily used to provide knowledge about foamed mix strength trends.

The first strength criterion evaluated was Hveem resistance. Figure 4 shows a graph of Hveem resistance versus bitumen content for foamed mixes at 6.0% moisture. Past studies by Bowering (59) and Bowering and Currie (60), found that with increasing bitumen content, Hveem resistance, CBR, and the cohesiometer value all reached maximum values at an intermediate bitumen content, and then decreased. The trend shown in Figure 4 was therefore very much anticipated. However, this study found that Hveem resistance was much less sensitive to changes in bitumen content than originally anticipated.

The modified Hveem stability test proved to be much more sensitive to changes in bitumen content. Figure 5 shows that stability values are significantly lower at the higher bitumen content. This stability test is considerably more rigorous than the resistance test. A stability value is obtained from the vertical application of 400 psi rather than the 160 psi used in the resistance test. This increase in pressure is responsible for the added sensitivity which differentiates strong from weak mixes. The modified Hveem stability test produces enough variance among mixes to be intelligently used as a criterion in the mix design process.

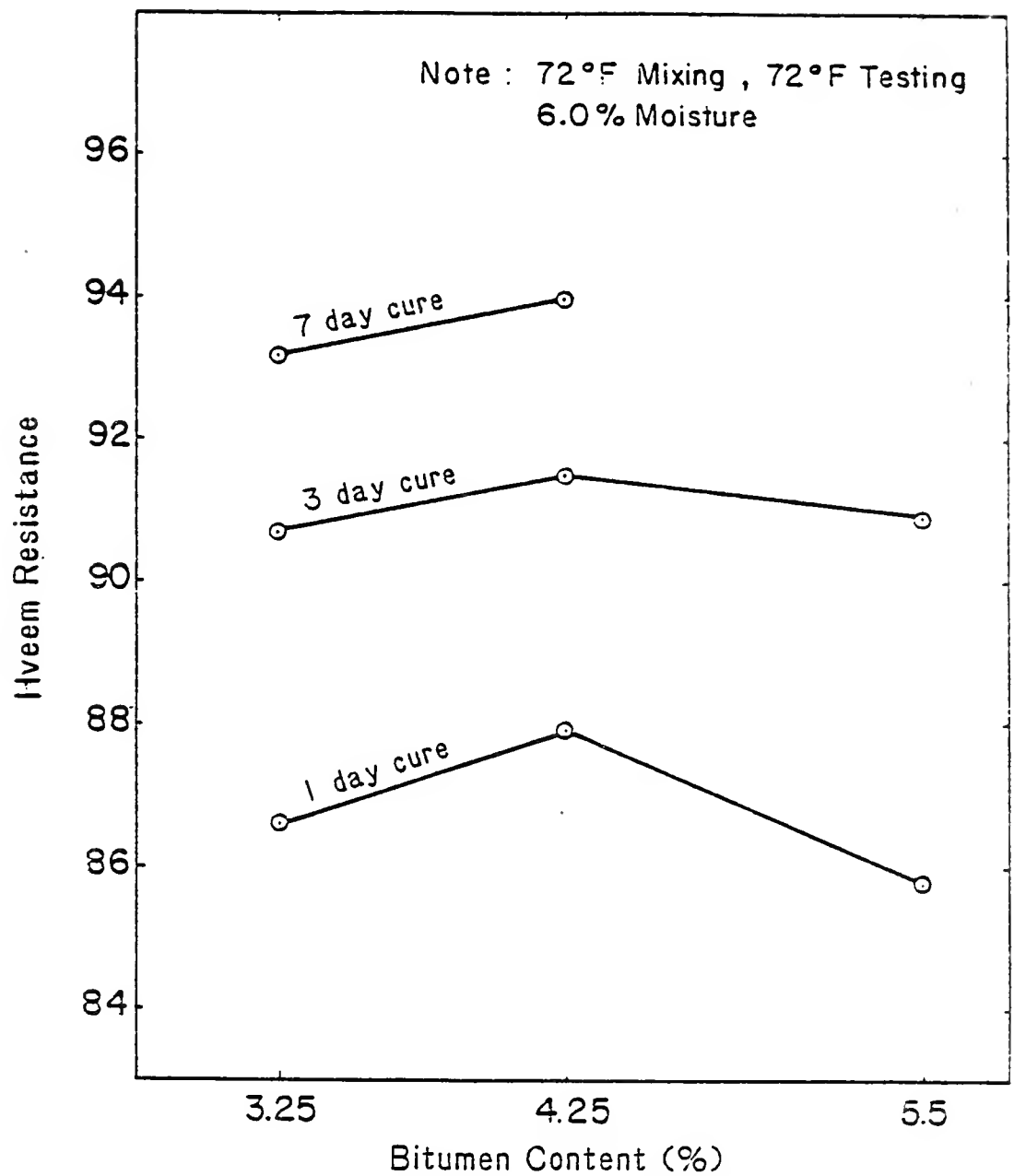


FIGURE 4 , HVEEM RESISTANCE AS A FUNCTION OF BITUMEN CONTENT AND CURING PERIOD (OUTWASH SAND).

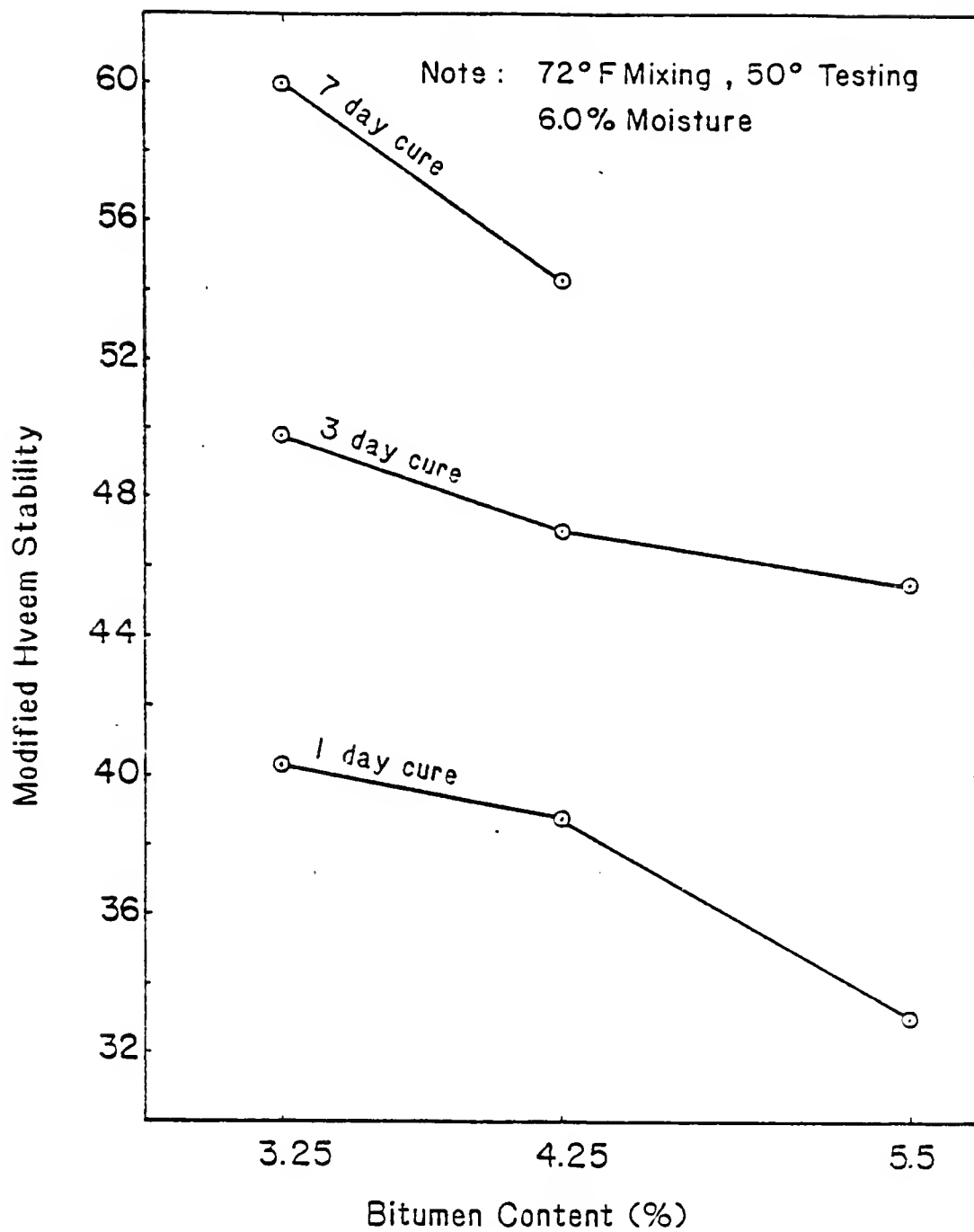


FIGURE 5 , MODIFIED HVEEM STABILITY AS A FUNCTION OF BITUMEN CONTENT AND CURING PERIOD (OUTWASH SAND).

Following the stabilometer tests, specimens were immediately placed in the Marshall testing machine. Figure 6 plots modified Marshall stability against bitumen content for three different curing conditions. In general, graphs such as this were irregular, showing that bitumen alone does not significantly affect Marshall stability in any consistent manner. However, a correlation may exist between total fluid content and Marshall stability. This idea will be investigated in the following section for possible use in the mix design. The Asphalt Institute suggests a minimum modified Marshall stability of 2500 lbs. for hot mixes subjected to medium traffic. The average stability for the foamed specimens in this study that were tested at 72°F and cured for 1 day was 2280 pounds. While it is difficult to compare these stabilities (Marshall compaction vs. kneading compaction), the values do provide some idea of strength.

Resilient modulus tests were performed on foamed mixes at their fluff point (6% moisture) as the final strength criterion. The results shown in Figure 7 verify the conclusion reported by Shackel et al (38), that a maximum exists for each set of conditions. This graph indicates an optimum bitumen content near 4% for the foamed mix studied. Although our resilient modulus data is limited, it appears to be one of the more appropriate tests for use in the mix design process. Like the Hveem stability test, resilient modulus data produces enough strength variance to select an optimum asphalt content.

The Effects of Moisture Content on Foamed Mix Strength. - The relationship between moisture content and the Hveem resistance test is an important aspect of this study. Previous studies (54) indicate that

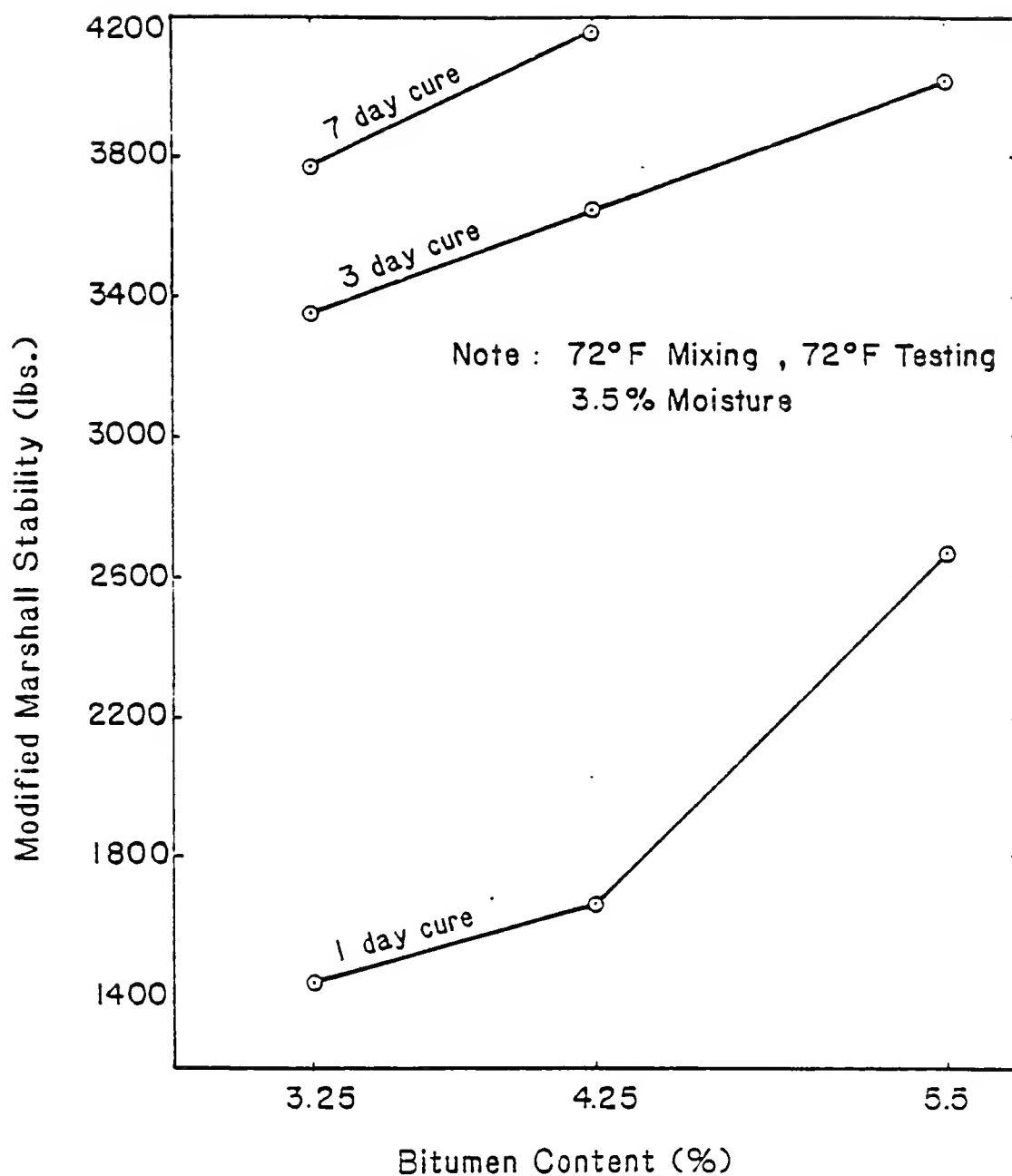


FIGURE 6 , MODIFIED MARSHALL STABILITY AS A FUNCTION OF BITUMEN CONTENT AND CURING PERIOD (**OUTWASH SAND**).

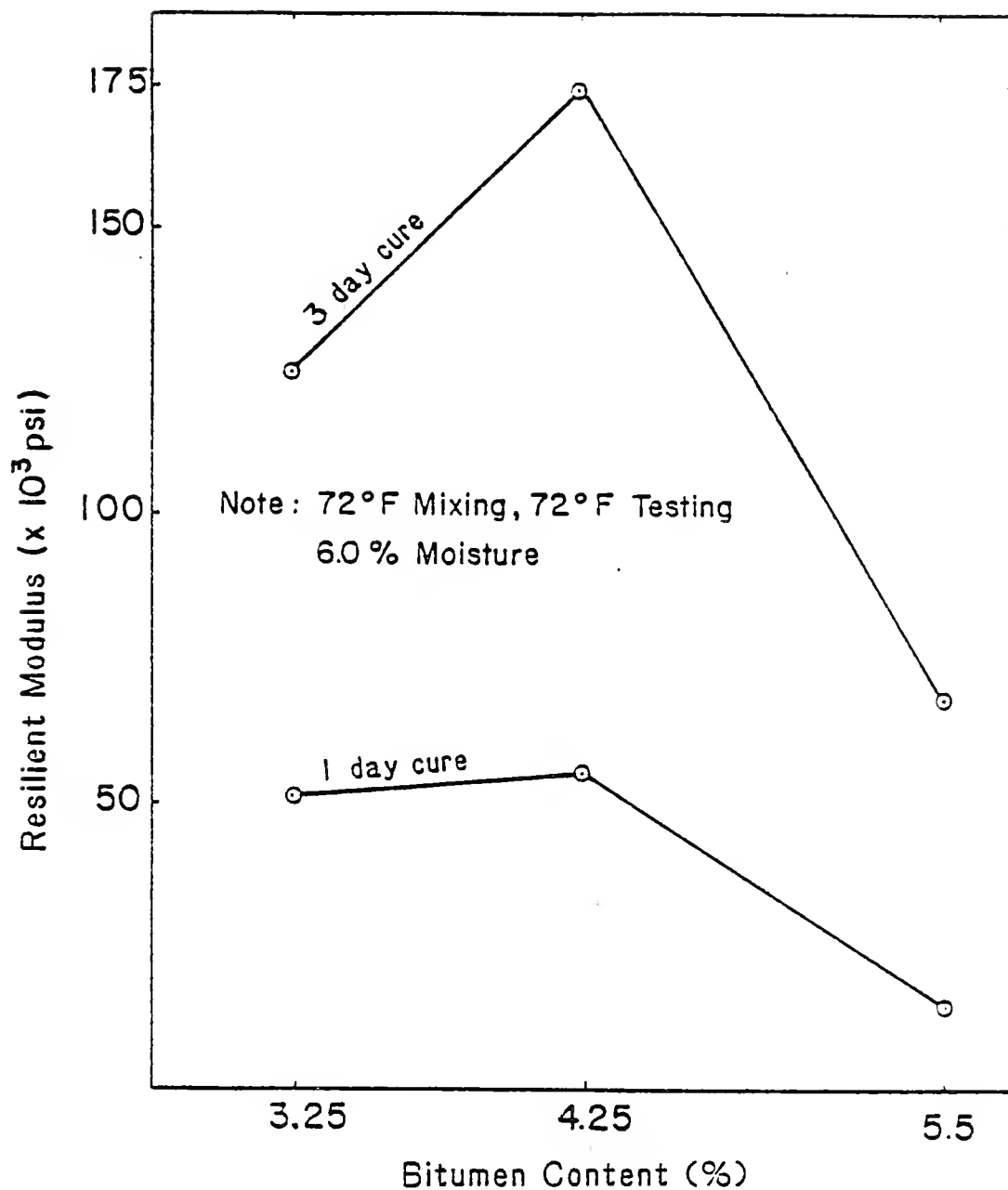


FIGURE 7 , RESILIENT MODULUS AS A FUNCTION OF BITUMEN CONTENT AND CURING PERIOD (OUTWASH SAND).

moisture content is the single most important factor in controlling the structural properties of foamed mixes. In addition, Hveem resistance is the primary measure of strength used for stabilized bases.

Figure 8 shows plots of Hveem resistance versus moisture content (at the time of mixing). The 3 day curing curves show that resistance values seldom vary by more than 1 or 2 units for a given bitumen content. These two graphs indicate that the foamed mix used in this study was relatively insensitive to changes in moisture over a significant range of moisture contents. This can be interpreted as a positive point in that moisture control is not as critical as previously expected. It appears that the foamed asphalt/outwash sand mix has an optimum moisture content somewhere between 4.75 and 6.0%, and possibly even higher. Since the fluff point produces optimum mixing conditions, the 6% moisture content would probably be selected for use under normal construction conditions.

The Effects of Temperature on Foamed Mix Strength. - Foamed specimens were tested at 50°F and 72°F. The effects of testing temperature on Hveem resistance of outwash sand-foamed asphalt mixtures, and its effects on the resilient modulus are shown in Figures 9 and 10. These graphs show that foamed mix strength was significantly greater at the lower testing temperature (50°F). From these results it can be inferred that foamed mix strength increases as the testing temperature decreases. The strength increase can be attributed to a stiffening of the mix at lower temperatures. The resilient modulus 1 day curing curves plotted in Figure 10 were the only test results in which strengths were comparable at 50°F and 72°F testing. This occurrence can possibly

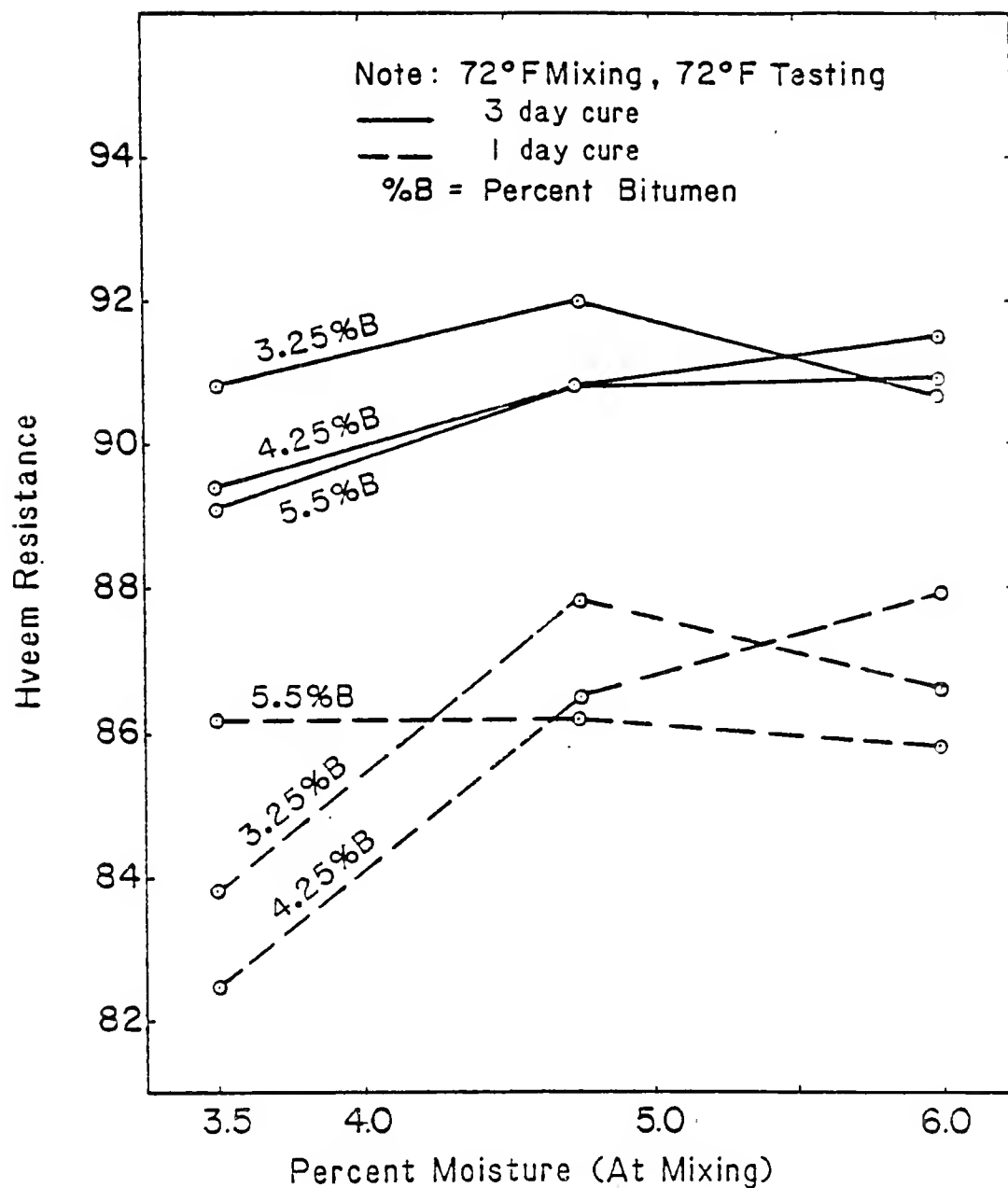


FIGURE 8 , HVEEM RESISTANCE AS A FUNCTION OF MOISTURE CONTENT, BITUMEN CONTENT, AND CURING PERIOD (**OUTWASH SAND**).

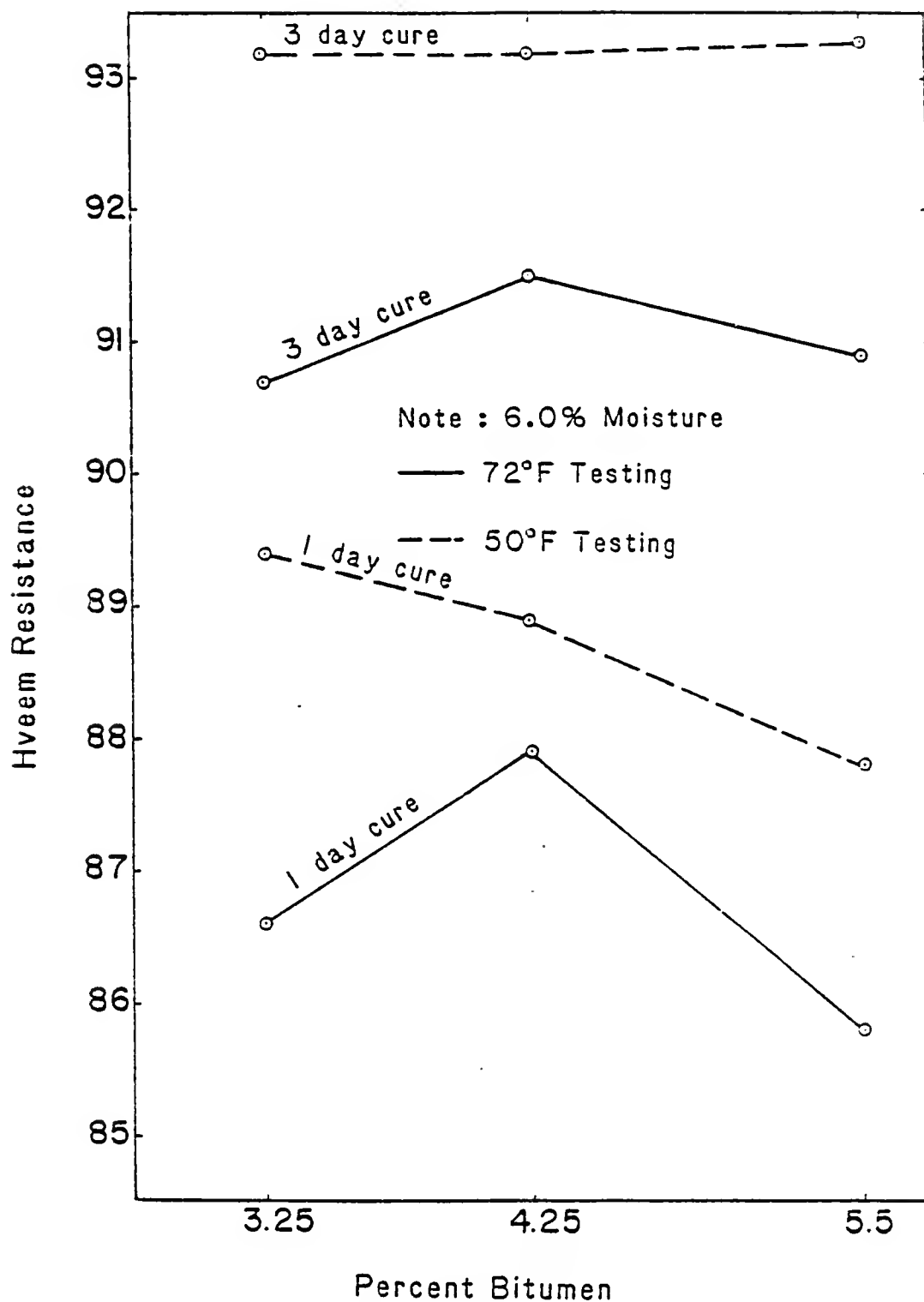


FIGURE 9 , THE EFFECTS OF TESTING TEMPERATURE AND CURING ON HVEEM RESISTANCE (OUTWASH SAND).

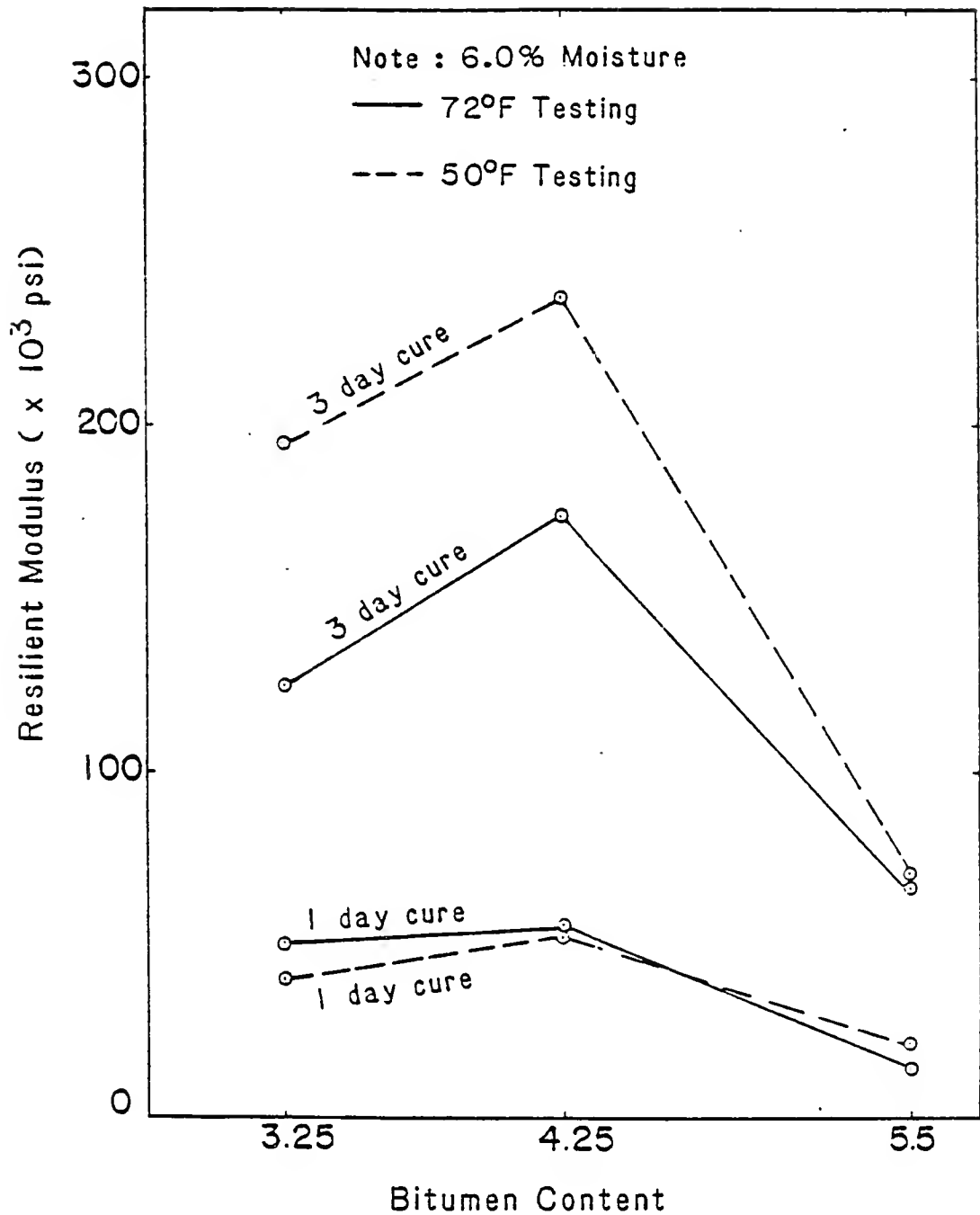


FIGURE 10 , EFFECTS OF TESTING TEMPERATURE AND CURING ON THE RESILIENT MODULUS (OUTWASH SAND).

be attributed to the erratic behavior found in many 1 day cured specimens, and the fact that foamed mixes are less temperature susceptible than other conventional mixes. However, these 1 day curing results are considered to be an exception rather than the rule.

The Effects of Saturation on Foamed Mix Strength. - The moisture sensitivity test created two problems which were not anticipated. The first problem was encountered when 1 day cured specimens crumbled during the 24 hour soaking period of the test. The specimens which crumbled had bitumen contents of 3.25% and 4.25%. The inability of 1 day specimens to withstand the soaking period caused the selection of a third and larger bitumen content, 5.5%. The second problem encountered was that certain specimens withstood the moisture sensitivity test, but swelled too much for testing in the stabilometer. It had been planned to use a testing sequence of Hveem resistance followed by Marshall stability. Swelled specimens which could not be tested for Hveem resistance were simply tested for Marshall stability. While the swelling of specimens prevented a more thorough comparison of data, it did highlight an interesting behavioral trend. Specimens fabricated at 6% moisture absorbed considerably less water than those made with 3.5% moisture, bitumen content being the same in each case. This was clearly evident at the two lower bitumen contents (3.25% and 4.25%) where specimens were much more susceptible to moisture infiltration. At these bitumen contents the 7 day cured specimens at 3.5% moisture swelled too much for stabilometer testing, while those with 6% moisture were successfully tested. It appears that foamed mixes should be compacted in the field at the highest feasible moisture content to best reduce the infiltration of water.

Figure 11 is a plot of modified Marshall stability against bitumen content for specimens subjected to vacuum saturation. This graph indicates that specimens fabricated at 6% moisture are slightly stronger than those fabricated at 3.5% moisture. After the observations about swelling, this was entirely expected. However, a much larger strength differential was anticipated. Note that the test values are relatively close for both moisture contents plotted. A possible explanation is that specimens at 6% moisture were significantly weakened by stabilometer testing, which accounts for the low Marshall stability values. Figure 42 also reinforces the concept that higher bitumen contents make for a more water resistant mix, which ultimately reduces strength losses due to soaking. Note the sharp increases in stability as the bitumen content increases from 4.25 to 5.5%. Foamed specimen behavior was markedly better at 5.5% bitumen. In fact, the 1 day cured specimens at 5.5% bitumen had slightly better R-values than 7 day specimens at the two lower bitumen contents.

A moisture sensitivity test is definitely needed in the mix design to indicate the limitations and weaknesses of foamed asphalt mixes. However, the particular method used in this study (vacuum saturation) appears to be excessively harsh on foamed mixes. For this reason, a less destructive type of moisture sensitivity test needs to be developed.

The test results obtained from this laboratory study are presented in this report by means of graphs along with the description of the parameters being measured. A complete list of these results is given in the Appendices section of this report. Throughout this description of the results, reference is made to tables and illustrations to be found in these Appendices.

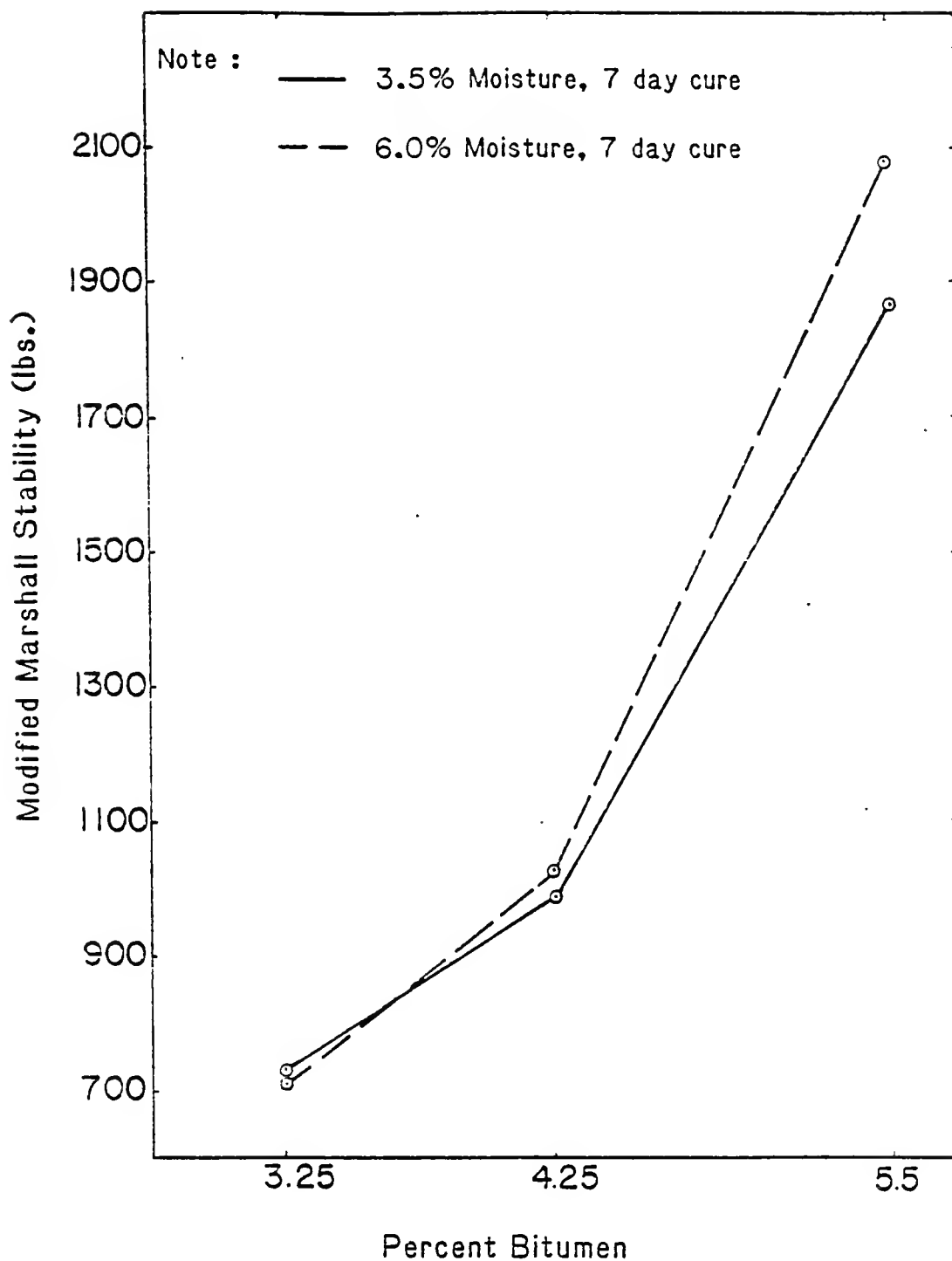


FIGURE 11 , MODIFIED MARSHALL STABILITY AS A FUNCTION OF BITUMEN CONTENT FOLLOWING THE MOISTURE SENSITIVITY TEST(**OUTWASH SAND**).

The next part of this study involves the use of two different types of aggregate material used in base course construction, pit run gravel and crushed stone. The test results obtained for foamed asphalt mixtures prepared with both of the materials mentioned before, will be presented and discussed next.

Pit Run Gravel-Foamed Asphalt Mixtures

Since both the Hveem R and S values measure the stability of the mixture, it is more convenient to consider them side by side. This will be done in the discussion of these two stability parameters for both of the aggregates considered in this part of the study. The Hveem R-value as well as the modified Hveem S-value are empirical numbers which measure the deformation of the specimen as a function of the transmitted lateral pressure to that of the applied vertical pressure.

It was observed that the effect of the initial moisture added (%W) was not very significant for the R-values, but was significant for the S-values. Plots of average R and S values versus %W for different asphalt contents (%FA) and curing times are presented in Figure 12 and Figure 13.

The effects of different mixing temperatures (FM), different FT, and %FA on the R-value and S-value of mixtures prepared at 3.9% W and 3 days cured were depicted in Figure 13. In all cases, smaller R and S-values were obtained for 50°F (10°C) mixing temperature specimens. Mixtures prepared at room temperature appear to give the same R and S-values of mixtures prepared at a high (100°F) temperature. Meanwhile, specimens tested at 72°F (22°C) for their R-value and S-value, gave larger rates for 3.25% FA mixtures than for mixes with 4.00% FA. R and S-values obtained at low FT didn't show any physical trend for

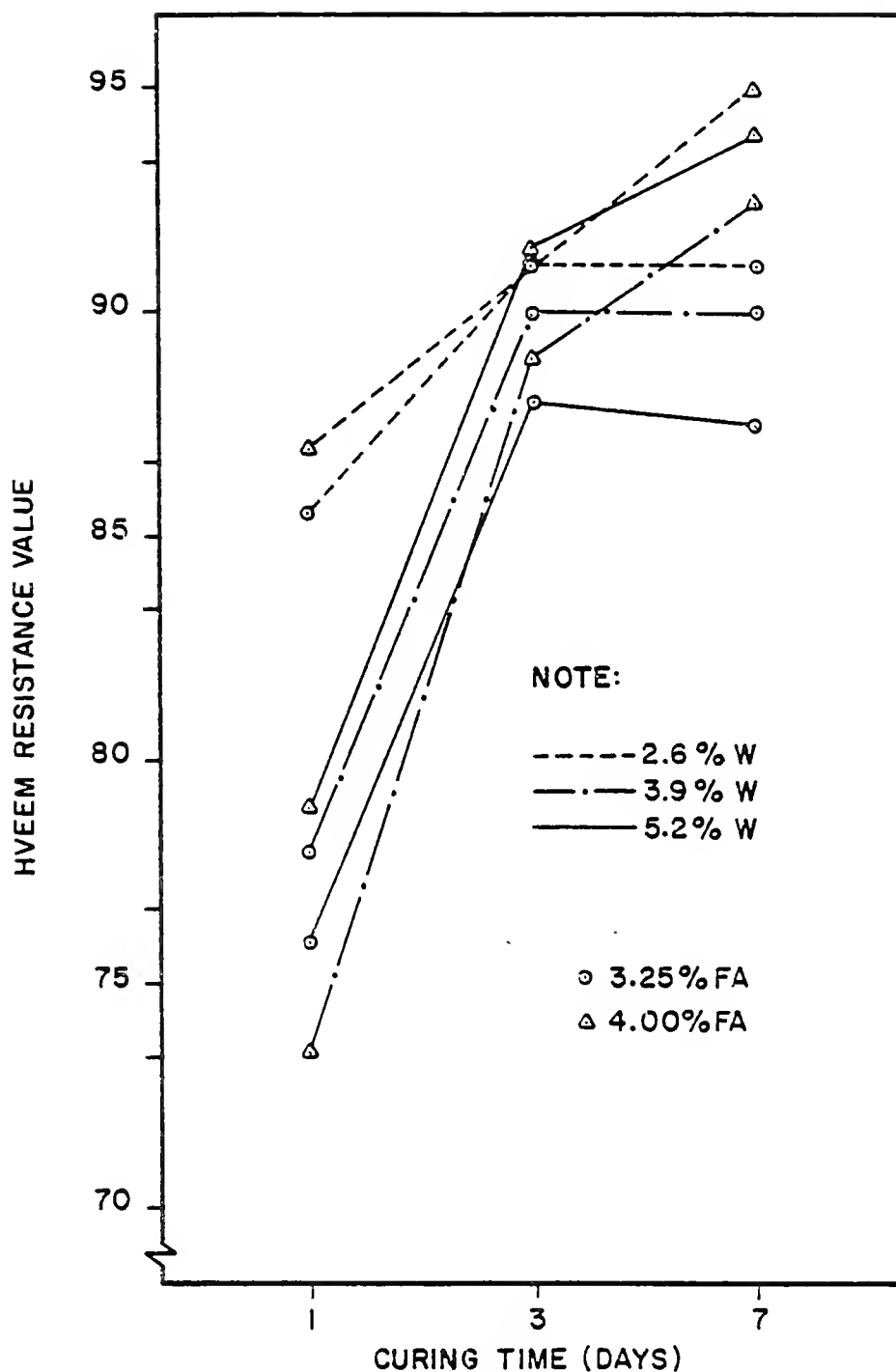


FIGURE 12 , EFFECT OF CURING TIME, INITIAL MOISTURE ADDED(% W) AND FOAMED ASPHALT CONTENT(% FA) ON THE HVEEM RESISTANCE VALUE AT NORMAL CONDITIONS FOR PIT RUN GRAVEL MIXES.

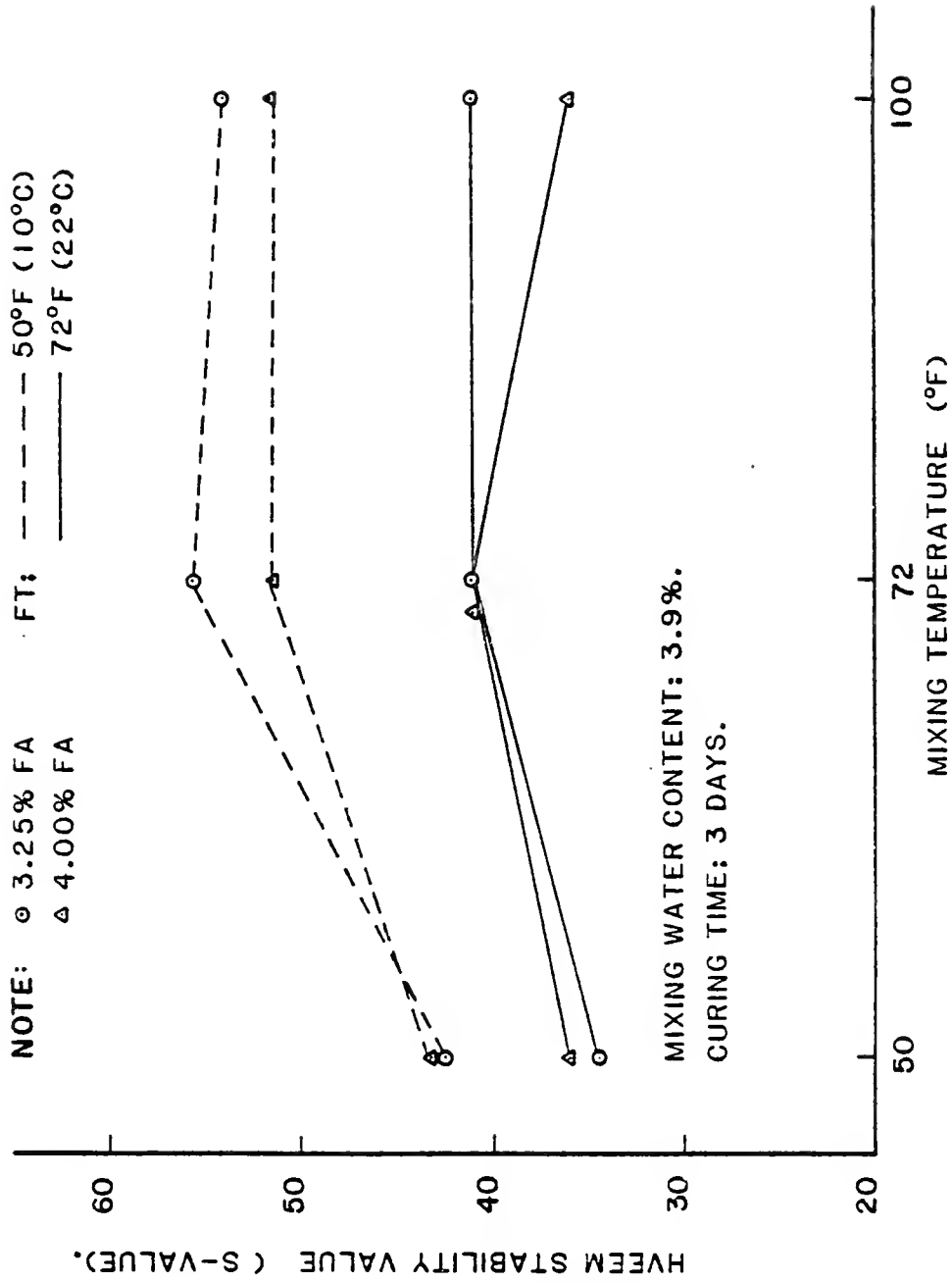


FIGURE 13 , EFFECT OF MIXING (FM) AND TESTING (FT) TEMPERATURES , AND FOAMED ASPHALT CONTENT (%FA), ON THE HVEEM S-VALUE OF PIT RUN GRAVEL MIXES.

both mix parameters at both levels of %FA. In all cases, larger R and S-values were obtained for 50°F (10°C) test temperature than for samples tested at normal conditions (see Figure 12 and Figure 13).

Increasing curing time from 1 to 3 days increased significantly the R-value (Figure 12) and the S-value (Figure 13) of foamed asphalt-pit run gravel mixtures. These effects of curing time and its interaction with %FA were reported by means of the influence of the total liquid content (%TL) on these two mix parameters.

The average Hveem Resistance (R-value), obtained for pit run gravel mixes in this study, was 84, with a maximum of 96.0 and a minimum of 72. The average modified Hveem S-value was 41.0, with a maximum of 57.5 and a minimum value of 24.5 for all the specimens tested dry. The lowest R-value obtained for a certain combination of factors as an average of 3 unsoaked samples was 72. This value was obtained using pit run gravel aggregate, with 4.00% FA at one day curing, and mixed at 50°F (10°C) under normal test temperature. According to commonly adopted design criteria in the State of Indiana (7, 26), the minimum R-value for dense graded initially cured bituminous mixtures used for base and subbase course, is 70. Furthermore, the criteria require a minimum R-value of 78 for final cured water soaked specimens. On the other hand, modified S-values obtained for foamed asphalt-pit run gravel mixtures couldn't be correlated with recommended limits of this value for base course material. However, minimum and average values obtained from this study can be considered satisfactory according to Hveem stabilometer test results reported in the literature (2, 29, 30).

Comparisons were made among the average Hveem R and S-values of two groups of specimens; specimens mixed at 72°F (22°C) and specimens

prepared at 100°F (38°C). For each mix combination, comparisons were made to the previous results of the dry test, and the percent retained R and S stability values were calculated.

It was noted that there is no significant difference in the effects of vacuum saturation, between the two groups of mixtures tested (72 and 100°F mixing temperature). Soaked specimens of pit run gravel mixes also showed no physical difference between the two levels of foamed asphalt added mixtures in the retained percentage of these two mix parameters. The modified S-value was reduced from 22% to 32% from its original value and the R-value suffered a reduction of only 6% to 9% due to the water saturation.

Finally, analyzing the test results obtained for these two types of aggregates, it can be found that the effects of curing were also insignificant. The R-value increased from 82 to 84, from 3 to 7 days air cured samples. Modified Hveem S-value showed also little improvement with the increasing of curing time.

Crushed Stone-Foamed Asphalt Mixtures. - The stability properties of the crushed stone-foamed asphalt mixtures was evaluated by means of the Hveem stabilometer test. Values of resistance to deformation as well as stability, were recorded following procedures and definitions described before in this laboratory report.

Hveem resistance (R-value) was greatly affected by curing and vacuum saturation among other factors considered. The same effects were also observed in the modified Hveem S-values obtained in this study. It was observed that the highest R and S-values were obtained when test temperatures were as low as 50°F (10°C) as depicted in Figure 14. Hveem values (R and S-values) were affected by %FA alone

(Figure 15), in an inconsistent way and no typical trend could be observed from this graph. Increasing the curing period increased these mix parameters as shown in Figure 14 (R-value). The curing time had greater significance in the S-values than in the R-values reported. Mixing temperature (FM) also was considered in the evaluation of the Hveem stability responses of crushed stone-foamed asphalt mixes.

The average R-value, obtained for crushed stone mixes was 91.0 from a range of values between 96.5 and 86.0. Maximum values of modified Hveem stability were 69.5, with minimums of 35. All these values were well above the recommended minimum Hveem parameters (2, 29, 30) for similar bituminous mixes used as a base course.

The analysis of the results in this set of experiments also considered the effects of the vacuum saturation. Comparisons were made among the average Hveem R and S-values of crushed stone mixes for the soaked and unsoaked conditions. It was noted that the mixture with 4.0% FA was affected in a significant way by the water sensitivity test, compared to mixes with 4.5% FA at any level of mixing temperature. Retained R and S-values for 72°F and 100°F mixing temperatures (FM) were presented in Figure 16. R-values for 3 days cured mixtures with 4% were reduced no more than 10% from its dry value at both FM mentioned before. On the other hand, modified S-values at any curing period and FM were significantly reduced by the action of water.

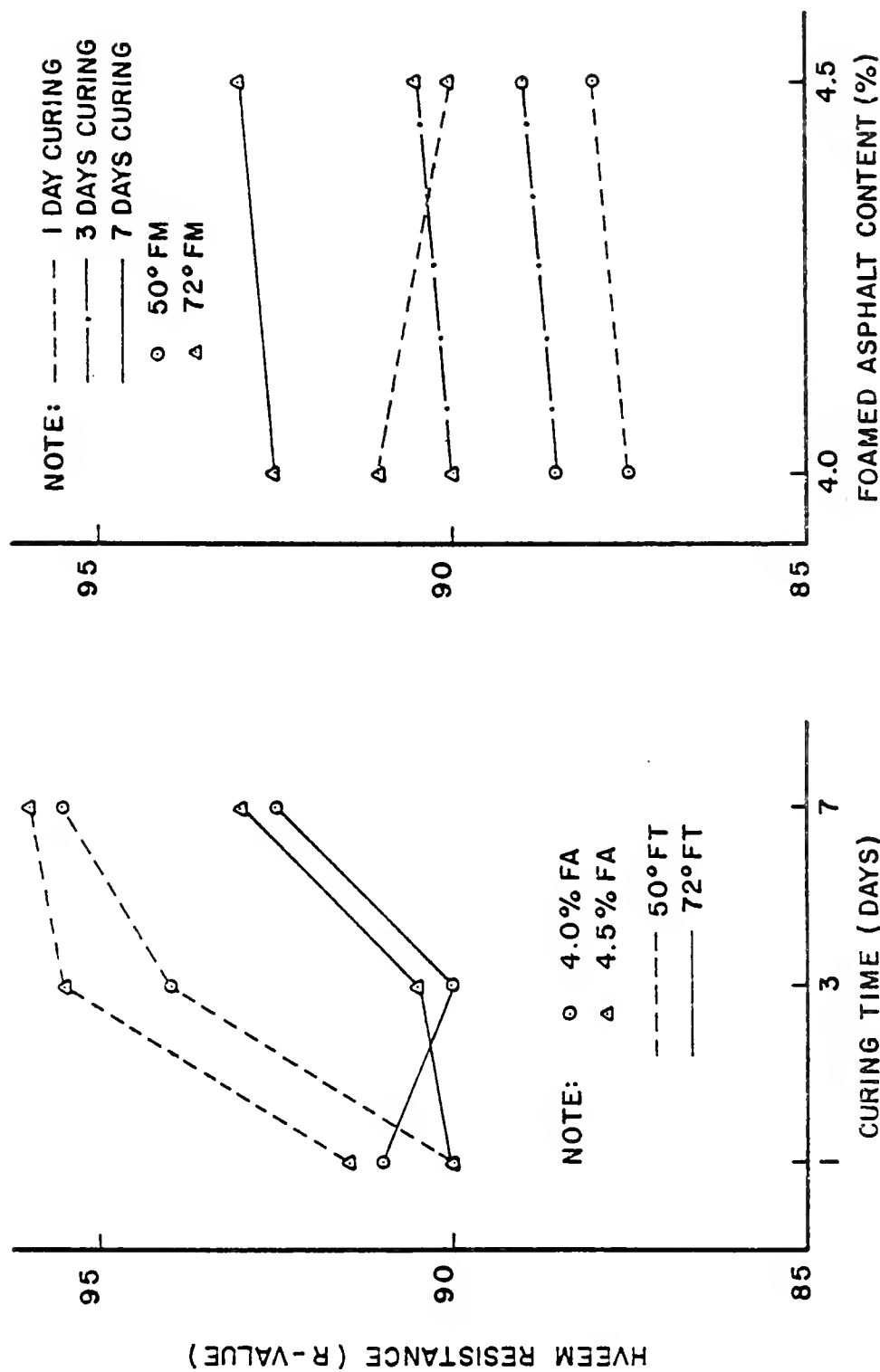


FIGURE 14 , EFFECT OF CURING, FOAMED ASPHALT CONTENT (%FA), AND TESTING TEMPERATURE (°F) ON THE HVEEM RESISTANCE VALUE OF CRUSHED STONE MIXTURES AT OPTIMUM MIXING WATER AND 72°F(22°C) MIXING TEMPERATURE.

FIGURE 15 , EFFECT OF FOAMED ASPHALT CONTENT, CURING, AND MIXING TEMPERATURE (°F) ON THE HVEEM RESISTANCE VALUE OF CRUSHED STONE MIXES AT 72°F(22°C) AND 4% MIXING WATER CONTENT.

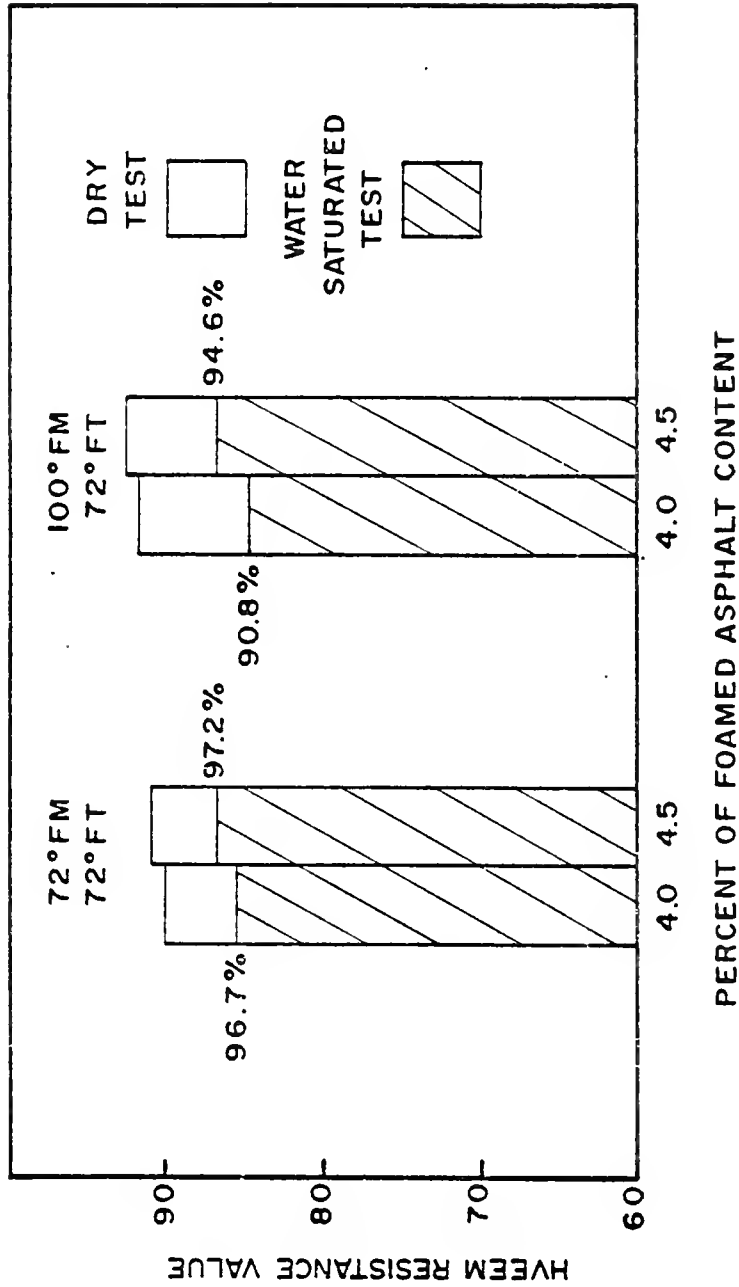


FIGURE 16 , RETAINED HVEEM R-VALUE AFTER WATER SENSITIVITY TEST FOR 3 DAYS CURED SAMPLES OF CRUSHED STONE MIXES, WITH OPTIMUM MIXING WATER AND NORMAL TESTING CONDITIONS.

SUMMARY OF RESULTS AND CONCLUSIONS

A detailed evaluation of the properties and performance of foamed asphalt-aggregate mixtures has been presented in this investigation. Three different base course aggregate types were analyzed together with three different amounts of initial moisture added, two different foamed asphalt contents, and three curing periods. In addition, the effects of using three different curing temperatures as well as two testing temperatures were also investigated. A recommended mix design procedure for preparing and testing foamed asphalt mix specimens was developed and used in the evaluation section of the study. It is reported in the last section of this chapter.

The evaluation of the properties of crushed stone, outwash sand, and pit run gravel-foamed asphalt mixtures, resulted in a number of test results. It must be recognized that those values obtained from foamed asphalt mixes were an outcome of a complex array of factors. Evaluating the mix properties as related to only a single factor is not sufficient. The interaction effects have also to be considered. Finally, it must be emphasized that the conclusions presented next pertain to the materials and testing procedures used in this laboratory study. The following is a brief summary of the significant findings of the study for the three types of foamed asphalt mixes that were analyzed.

Conclusions for Outwash Sand Mixes

1. Outwash sand can be successfully used with foamed asphalt to produce a strong stabilized base course. To insure satisfactory performance, the base course should be properly drained and sealed to prevent moisture infiltration.
2. Foamed mix strength increases with curing time. A significant strength increase was realized from 1 to 3 days; 3 day strengths were approximately the same as 7 day values. Satisfactory strengths were produced at low curing times (1 day); an obvious advantage over emulsions and cutbacks which require formidable curing periods.
3. Kneading compaction produced high quality foamed specimens with dry densities ranging from 122.8 to 126.6 pcf. This represents an increase of approximately 15% over the non-stabilized outwash sand maximum density of 108.5 pcf.
4. The selection of an optimum bitumen content should be primarily based upon results from the modified Hveem stability and resilient modulus tests. For this foamed asphalt/outwash sand mix, maximum strengths were generally obtained at bitumen contents between 3.25 and 4.25%.
5. Foamed mix strength was found to be somewhat insensitive to differences in moisture for the range of

moisture contents studied (3.5% to 6.0%). Results from the entire testing sequence indicate the existence of an optimum moisture content between 4.75 and 6.0%. Compaction at moistures near the low end of this range ($\approx 4.75\%$) produced the highest early (1 day) strengths.

6. A total fluid content near 10.5% produced exceptionally good Hveem resistance and modified Marshall stability data. Strength values obtained from these tests generally reached a maximum near this total fluid content. Note that this total fluid content is near the outwash sand's optimum moisture content of 11.4% determined by the standard Proctor test (ASTM D698).
7. Foamed specimens tested at 50°F were substantially stronger than those tested at 72°F. It can be inferred that foamed mix strength increases as testing temperature decreases. The effects of mixing temperature on foamed mix strength were often insignificant. Strength values were quite satisfactory at the lowest mixing temperature (50°F).
8. Specimens subjected to the moisture sensitivity test showed greatly improved strength values at the highest bitumen content, 5.5%. Lower bitumen content specimens showed significant degradation during vacuum saturation.
9. Foamed mixtures should be compacted at the highest feasible moisture content to reduce water infiltration.

Conclusions for Pit Run Gravel Mixes

A comprehensive summary of the laboratory results obtained for compacted test specimens of this type of foamed asphalt mixtures as well as a complete tabulation of the laboratory data, may be found in the Appendix section of this report. According to the observations and test data, the following conclusions were determined.

1. The foamed asphalt coating on pit run gravel particles was principally affected by the mixing water added to the aggregate during this process. A recommended range between 2.6% and 5.2% by dry weight of aggregate that included the "fluff point" of the material (3.9% W) was found to be the most suitable to promote the asphalt distribution and coating action of this material. Visual inspection during the mixing and compaction process were utilized for this purpose.
2. The pit run gravel-foamed asphalt mixture performance was sensitive to temperature. Lower test temperatures increased the resilient modulus, Hveem stabilometer and Marshall test values. On the other hand, the effects of different mixing temperatures on the density and strength characteristics of this type of mixture were often insignificant. However, a slight decrease in performance was observed for mixtures prepared at low mixing temperatures, while slightly better test results were obtained when mixing at normal and high temperatures. The lack of influence of this factor

is believed to be due to the fact that the range of temperatures considered (50°F to 100°F) was not sufficiently wide to show any consistent correlation between this variable and the various strength parameters.

3. Specimens subjected to the water sensitivity test or/and early cured (1 day), were difficult to test at any testing temperature. Cracks developed in those groups of test samples before the resilient modulus test was completed. Difficulty in performing the other test methods considered in this study was not encountered for any mix combination.
4. Pit run gravel-foamed asphalt mix density and strength characteristics increased with curing time. A significant strength increase was realized from 1 to 3 days air curing. Three days strengths were approximately the same as 7 days values in most cases. Satisfactory strengths were produced at early curing period (1 day). All values were well above normally specified minimums. This is an obvious advantage over emulsion and cutback treated mixtures which require long curing periods.
5. The percent moisture retained in the sample is a function of foamed asphalt content, added moisture content and curing time; with the curing time having a greater bearing on the amount of moisture retained, principally at high levels of foamed asphalt and mixing water contents.

6. Both asphalt and initial moisture contents and their interaction significantly affected the dry and wet unit weights of pit run gravel-foamed asphalt mixtures. The optimum total liquid at time of compaction that provided maximum dry densities was lower than that required to provide a maximum wet unit weight.
7. The wet unit weight of the mixture was changed according to the change in total liquid content at time of testing. The total liquid content on the other hand was affected by the curing periods of the mix. Early cured specimens showed higher percentages of total liquid than samples submitted to the ultimate curing condition.
8. Higher dry unit weight as well as lower total air voids content (denser mixtures) were provided by 4.00% foamed asphalt contents and 3.9% initial moisture added for test samples at any mixing temperature. Dry densities as well as voids content remained unaltered by curing, and it is believed that they are a function of the fluids added to the mix as well as the compactive effort applied during the compaction process.
9. The effect of the initial moisture added on the amount of retained moisture after curing was more apparent at early curing stages. The mixture workability for the materials and methods of preparation used in

this study were also affected by this mix variable (initial moisture added).

10. The effects of water on the pit run gravel-foamed asphalt mix properties were tested using the water sensitivity test. The effect of water on the foamed asphalt mixtures increased with decreasing total foamed asphalt contents and curing time allowed. The effects of vacuum saturation were also related with the amount of moisture absorbed during the water sensitivity test. This moisture absorbed during vacuum saturation was directly related with the amount of total voids content of the mixture. A high voids content implies higher amounts of water absorbed.
11. The pit run gravel-foamed asphalt mixtures were suitable to be tested using the Hveem Stabilometer and Marshall test procedures at room temperature. Both Hveem R and S-values obtained from the test were largely affected by curing and foamed asphalt contents, as well as test temperatures.
12. It is believed that the selection of an optimum bitumen content should be primarily based upon results from the modified Hveem stabilometer and resilient modulus test procedures, as well as based on the vacuum saturation effects. Pit run gravel-foamed asphalt mixture, a cold mix type of bituminous mix, had better waterproofing characteristics for foamed asphalt

contents above 4.00% (by dry aggregate weight).

However, good strength was already imparted to this type of material at levels of 3.25% of foamed asphalt content.

13. Curing time as well as test temperatures were the controlling factors for the properties of this type of foamed asphalt mixtures. Some correlation was also noted between foamed asphalt content and initial moisture added and strength parameters of the mix. The effects of different mixing temperatures as considered in this study (50°F to 100°F) were in general insignificant on the performance of this type of cold mixture.
14. Finally, it can be concluded that pit run gravel aggregate material can be successfully stabilized with the foamed asphalt process as a suitable base or subbase course for pavement construction. However, to insure satisfactory performance, the base or subbase course should be properly drained and a wear course placed on top of it, to prevent moisture infiltration.

Conclusions for Modified Class 5-D Base Aggregate (Crushed Stone) - Mixes

Based on the results of the entire set of crushed stone-foamed asphalt mix test specimens used in this study; prepared and tested as described before, the following conclusions can be postulated:

1. Many of the response variables obtained for this type of mix are dependent on the amount of liquid present

at the time of the test. Thus, the effect of the liquid present in the specimen will be dependent on all its components. In most cases these components will be foamed asphalt and moisture contents as affected by curing periods and test or mixing conditions.

Similar trends and influences were described in the section presented before for pit run gravel mixes.

2. It was found that the ultimate curing condition did give strength results significantly different from the results of the early curing conditions. This difference could be used to establish minimum strength criteria for crushed stone-foamed asphalt mixtures. The manner this should be done would be dependent on field procedures and performance. The selection of two curing conditions should be adequate.
3. The results of this study on crushed stone-foamed asphalt mixes support the conclusions found in the literature review concerning the water sensitivity test. This test should be used in the evaluation of this type of foamed asphalt mixture. The test gives a better representation of the true effects of the factors involved in the investigation. It also indicates the actual mix properties under adverse conditions. A minimum unsoaked strength as well as a minimum retained strength criteria should provide adequate control of the crushed stone-foamed asphalt mix performance.

4. The coating and workability, as well as the compacted density and voids content of crushed stone mixes were affected by the amounts of moisture and foamed asphalt added. Four % by weight of dry aggregate, of mixing water, with levels of foamed asphalt between 4.0% and 4.5% appear to give optimum results for these mix parameters (dry and wet unit weights, voids, moisture and total liquid content). Somewhat higher amounts of bitumen were required for crushed stone mixes than for mixes prepared with gravel because of the larger surface area observed in the coarser fractions of the crushed stone material. However, similar or better strength characteristics were observed for crushed stone mixes as compared with the other foamed asphalt mix investigated in this study.
5. Testing temperatures and curing time influenced the mix performance greatly. All mix parameters recorded showed that decreasing the test temperature, or/and increasing curing time, the strength properties of crushed stone were greatly improved and higher resilient modulus, Hveem R and S-values as well as Marshall results were obtained. The influence of mixing temperatures were insignificant and in general they didn't correlate with the other factor and parameters observed.

6. The same advantages observed for foamed asphalt mixes prepared with gravel could be attributed to crushed stone-foamed asphalt mixes. They both can successfully perform as base or subbase course in a pavement system, when properly drained and sealed. All values obtained showed that minimum requirements were met for most of the test parameters measured.

Based on observations obtained from all three foamed asphalt mixtures investigated, the final conclusions are as follows:

Asphalt was recovered from several test specimens using the procedure outlined by the "Recovery of Asphalt From Solution by Abson Method", ASTM D1856.

Each sample recovered was tested for consistency by penetration and kinematic viscosity, using the appropriate standard procedures for each test (ASTM D5, and ASTM D2170) respectively. The results obtained in all cases showed that there were no changes in the asphalt properties due to the foaming process. There was also found that the real amounts of asphalt added to the mixture were very close to the expected quantities, and therefore, no adjustments in the calculated test values were required. Finally, the gradation of the recovered aggregate was checked, showing little or no departure from the original gradation.

Recommended Laboratory Mix Design Procedure for Foamed Asphalt Mixtures

This procedure covers the selection, proportioning and testing of components of foamed asphalt paving mixtures to be used in base and

subbase applications. This recommended method, basically follows procedures developed within the Asphalt Institute (7), Mobil Oil of Australia Ltd., CONOCO; and test methods developed by the California Division of Highways.

Its application is recommended for the foamed asphalt-cold mix production with materials available in the State of Indiana; and its feasibility is based on the experience gained from this study as well as the findings and results obtained from other laboratory investigations as reported in the Review of the Literature in this report. Also, the test procedures employed in this study were considered effective in evaluating the properties of this type of cold mixture. Next is a summary of the suggested mix design procedure:

1. Aggregate Quality Evaluation

Thorough testing of the aggregates is necessary in order to determine its suitability for use with foamed asphalt. Aggregate properties are among the principal factors for the production of an optimum mixture. Crushed stone, gravel, rock, sand, silty sand, sandy gravel, and recycled material, are reported as being suitable for their stabilization and the use of foamed asphalt as a binder material.

Some recommended test procedures used to evaluate the aggregate properties are as follows:

- * ASTM C29 - Test for Unit Weight of Aggregate.
- * ASTM C127 and ASTM C128 - Test for Specific Gravity and Absorption of Coarse Aggregate, and Test for Specific Gravity and Absorption of Fine Aggregate.

- * ASTM C136 - Test for Sieve or Screen Analysis of Fine and Coarse Aggregates.
- * ASTM D423 - Test for Liquid Limit of Soils.
- * ASTM D424 - Test for Plastic Limit and Plasticity Index of Soils.
- * ASTM D698 or ASTM D1557 - Test for Moisture-Density Relations of Soils, using 5.5-lb Rammer and 12-in Drop, or Test for Moisture-Density Relations of Soils Using 10-lb Rammer and 18-in Drop.
- * ASTM D2487 - Classification of Soils for Engineering Purposes.

Control tables for aggregate gradation ranges and plasticity, among other properties of the mineral material, are reported in the references related with the foamed asphalt technique. The classification of aggregates under both the AASHTO and Unified systems is recommended to facilitate correlation of laboratory and field results obtained in different places.

2. Foam Quality Evaluation

Not all asphalt cements are suitable for producing foamed asphalt. Anti-stripping agents and other additives may be added to asphalt cements that contain silicone or chemicals that reduce its foaming capacity. Uniformity in terms of the same source (oil refinery), and grading of this binder material, are required in order to obtain homogeneous mixtures. Related ranges of foaming temperatures and amounts of water injected should be carefully studied

prior to deciding the best combination of asphalt source, asphalt grade, and temperature as well as amount of foam water, for a specific type of foamed asphalt mixture (refer to Reference No. 11).

The grade of asphalt cement to be used depends on the type of pavement and the specific service conditions considered. A laboratory foamed asphalt dispenser is required for the earliest evaluation of the most suitable material to be foamed as well as for the determination of the inter-related operating levels of asphalt temperature and foaming water addition rates.

Asphalt temperatures of about 325°F (160°C) are typical, but may range from 300°F (150°C) to the maximum of 375°F (190°C) for high viscosity grade asphalts. Half life and expansion ratio ranges are wide and difficult to predict due to the fact that these two parameters have interactive effects between each other, and with all the variables related with the asphalt cement itself. It can be stated that the most acceptable values of foam ratio and half life of the foam, are the ones obtained with the most economically available asphalt cement types and sources, for a determined type of work and location. Therefore, foamed quality tests must be performed on available binder materials, selecting the required temperature and foaming water rate that would yield the best combination of half life and expansion ratio values. However, a search in the related literature (11, 31), indicates recommended ranges for expansion ratio 6 to 20, and half life of 30 to 80 seconds.

Other test results such as specific gravity, etc., are required in order to characterize the asphalt cement used in this stabilization process, as well as for the determination of useful mix parameters such as air voids content, etc.

Typical standard tests performed for asphalt characterization are as follows:

- * ASTM D5 - Test for Penetration of Bituminous Materials.
- * ASTM D36 - Test for Softening Point of Bitumen (Ring and Ball Apparatus).
- * ASTM D70 - Test for Specific Gravity of Semi-Solid Bituminous Materials.
- * ASTM D113 - Test for Ductility of Bituminous Materials.
- * ASTM D1856 - Test for Recovery of Asphalt from Solution by Above Method.
- * ASTM D2170 - Test for Kinematic Viscosity of Asphalts (Bitumens).

3. Selection of Mix Proportions

The determination of the optimum moisture content (OMC) of the aggregate type to be stabilized, as well as the "fluff point" moisture content of it, are required in order to determine the optimum amount of moisture that should be added to the mixture for mixing and compaction purposes.

This selection of optimum moisture added for mixing and laydown, should be based on maximum density achieved for three or more mixes made at a trial asphalt content that can be chosen from recommended values encountered in the related literature. The table "Trial Asphalt Content", reported

below, is recommended in CONOCO's proposed Foamix design method.

RECOMMENDED TRIAL ASPHALT CONTENT (After CONOCO's proposed Foamix design procedure)

<u>% Pass. 200 Mesh</u>	<u>Less Than 50% Pass. #4</u>	<u>More than 50% Pass. #4</u>
3.0 to 5.0	3.0	3.5
5.0 to 7.5	3.5	4.0
7.5 to 10.0	4.0	4.5
More than 10.0	4.5	5.0

Recommended values for this parameter also are reported by the Asphalt Institute (7), and Mobil Oil among others. The mixtures made with the appropriate trial foamed asphalt content, should be prepared with moisture levels somewhere between 40 to 80% of the aggregate OMC as determined by ASTM D698 or ASTM D1557 (refer to Section 1 of this recommended procedure). A range of mixing water from the minimum of 1.5 percent less than the "fluff point", to a maximum of 1.5 percent more than this aggregate moisture content, is also recommended.

Considerations regarding the maximum size of the aggregate should be taken for the preparation of this type of cold mixture. Separate and omit all 3/4 in. plus fraction from mixing batch but include in final calculations. If the aggregate material maximum size is 3/8 in. or more, separate all aggregate test batches into plus #4 and minus #4 sieve fractions. Apply foamed asphalt to minus #4 fractions of batch at desired moisture level, and mix about 2½ minutes

in mechanical mixer. Add plus #4 portion of batch which has been premoistened with fine moist spray, to batch and complete mixing by hand with spoon for 30 seconds. Broken or locked blades may result if trying to mechanically mix above #4 sieve maximum size aggregates. However, every effort should be made to add the foamed asphalt to the whole batch of inert material.

Immediate compaction of the mixture should follow next to avoid loss of the required moisture for compaction purposes.

The determination of the theoretical or estimated optimum foamed asphalt content, trial asphalt contents should be used with the selected optimum moisture added, to prepare sets of three specimens to be tested for:

- Optimum fluid for compaction (7).
- Visual examination of cured and loose mix sample as well as during mixing and compaction process.
- Density of the compacted samples.
- Stability properties of the mix (either Hveem or Marshall Method).

Other applicable test procedures for cold asphalt mixtures might be applied based upon experience. Normally, laboratory tests will be conducted for four bitumen contents. The incremental changes in bitumen content should be 0.5 percent (2). Finally, the number of tests and the incremental changes in foamed asphalt contents may be varied to satisfy unusual conditions.

The total batch weight, including bitumen, shall be that necessary to produce a specimen 4 in. in diameter and 2.5 ± 0.1 in. high. Typical amounts of 1100 gr. to 1200 gr. total mix are satisfactory.

4. Sample Preparation

The foamed asphalt mixtures are to be prepared at two or more levels of asphalt in the trial asphalt content midrange, and all at the optimum initial water added for mixing and compaction purpose. Three or more levels of mixing water should be used.

The compaction of the mixture should be followed next. For this purpose, the Hveem kneading compactor as well as the gyratory machine can be used. A final compactive effort of 500 psi (3.45 MPa) can be used for the kneading compactor (4), and a compactive effort of 40 revolutions at 200 psi (1.38 MPa) is believed to be appropriate when using the gyratory machine in accordance to ASTM D3387-74T (42).

The criteria for the curing of the specimens should be, to leave in the mold at room temperature for 24 hrs. before extrusion. Three and seven days cured specimens as well as 24 hrs. in the mold samples, should be tested to obtain their representative properties at various stages and conditions as submitted by traffic and environment when in service.

For more practical consideration, the early cured condition (24 hrs. in the mold at room temperature) for hauling traffic, and construction purposes is recommended. The seven

days cured mixture, or long term cure (24 hrs. in the mold before extrusion) should be the "ultimate" condition before test procedures are applied for characterizing the compacted mixture.

5. Recommended Testing Procedures

The compacted and cured specimens are to be tested in the diametral resilient modulus testing device. The compacted samples would next be tested in the Hveem stabilometer for their Hveem resistance value and their modified stability value. After the stabilometer test, the specimens can be tested in the Marshall testing machine to obtain the stability, flow and stiffness of the compacted foamed asphalt mixture. However, this applies principally for samples cured for three or seven days that are strong enough to withstand the MR and stabilometer test, practically undeformed.

Problems have been found when this sequence of test procedures (MR, Hveem stabilometer, and Marshall) was tried in water saturated or early cured specimens. The resilient modulus (MR), even though is a nondestructive type of test, appears to be too severe when performed in weak specimens previously soaked in water. Large deformations and frequent occurrence of cracks suggested the omission of this test in such weak samples, or the performance of a triaxial type of test such as the Hveem stabilometer. The performance of test procedures in samples of the early cured condition, and in water saturated specimens should be made in virgin

samples prepared for each individual test method. The use of already tested specimens could result in worthless results.

Finally, the water sensitivity test as modified from the suggested Asphalt Institute method, is to be used to determine the effect of moisture on the compacted foamed asphalt mixtures. In this test, the specimens to be tested are placed in a vacuum chamber and are subjected to a vacuum of 30 mm. Hg for one hour. At the end of this period, 72°F (22°C) water is slowly drawn by the vacuum into the chamber until the specimens are submerged at least a half inch below the water surface. The vacuum is released and the specimens are left to soak for 24 hours.

6. Evaluation of Test Results

The evaluation of test data obtained from the dry and water sensitivity tests (resilient modulus, Hveem stabilometer, and Marshall test), can be compared to evaluate the performance of the compacted foamed asphalt mixture. Also the effects of the different variables involved in the determination of the optimum mix parameters can be concluded from these test results.

For relatively stable mixtures, the Hveem R-value is quite insensitive to the changes in mixture variables such as water and foamed asphalt contents, etc. The Marshall or Hveem stability values will help to overcome this problem and should be sufficient for the evaluation of compacted foamed asphalt mixtures.

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APPENDICES

There is a supplement of nine appendices for this report. These appendices are listed in the LIST OF CONTENTS, and copies of any of them can be obtained by writing to:

Joint Highway Research Project
School of Civil Engineering
Purdue University
West Lafayette, Indiana 47907

